JANUARY 1961

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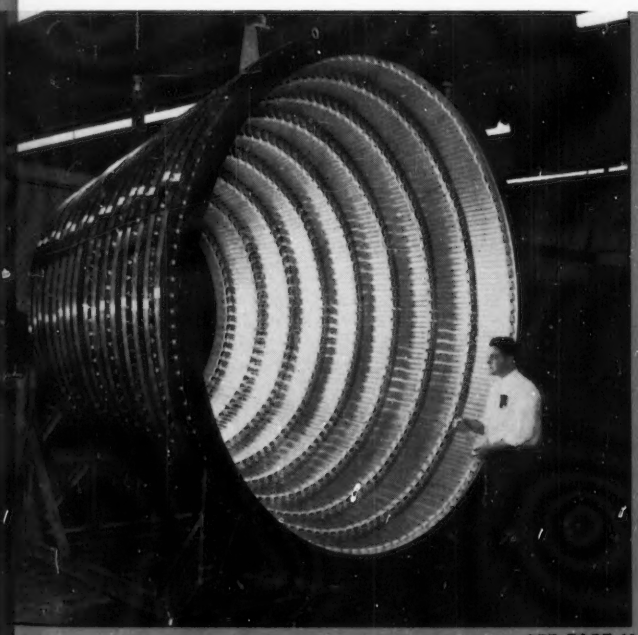
experimental mechanics



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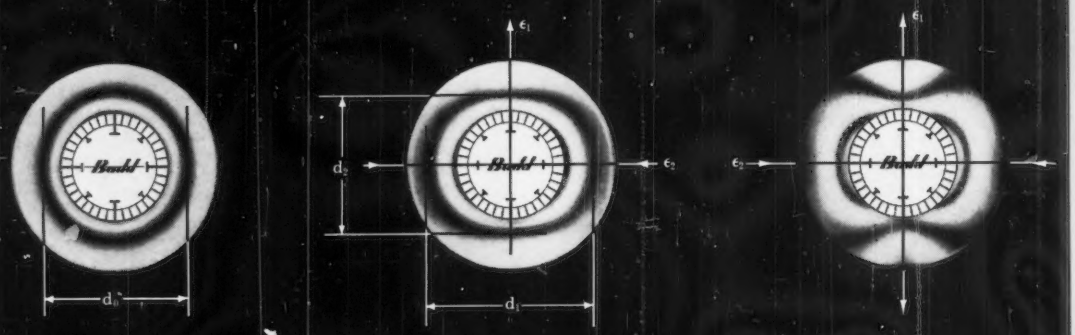
SESA JOURNAL OF THE SOCIETY FOR EXPERIMENTAL STRESS ANALYSIS



NEW! PhotoStress Rosettes* from Budd

THE ONLY GAGES THAT PROVIDE DIRECTLY BOTH ORIENTATION AND SEPARATE MAGNITUDES OF PRINCIPAL STRAINS

*Developed from original circular photoelastic gage patented in France in 1956 by Dr. G. Golubovic of PhotoStress France, U.S. patent pending.

Gages shown actual size. ϵ_1 and ϵ_2 are principal strains. d_o is diameter of circular fringe for zero strain. $d_1 - d_o$ and $d_2 - d_o$ give fringe shift along axes of symmetry of patterns, due to strain. Axes of symmetry are principal strain directions. ϵ_1 is a function of $d_1 - d_o$. ϵ_2 is a function of $d_2 - d_o$.

EXCLUSIVE FEATURES:

- Measures principal strain directions for strain levels as low as 50 microinch/inch and up.
- Major and minor principal strain directions obviously apparent.
- Separate magnitudes of strains obtained directly along desired axis.
- High readout sensitivity due to permanent pattern.
- Constant sensitivity for directions and magnitudes for any strain level.
- Proved PhotoStress technique (Zandman method).

GENERAL FEATURES:

- Direct readout, no instruments or connections.
- Static or dynamic (with strobe light) readings.
- Sensitivity and zero stable with time, unaffected by humidity.
- Easily bonded at room temperature to metals, concrete, wood and other materials.

SPECIFICATIONS:

- Directions of principal strains: within ±5° (with care, better accuracies are possible).
- Magnitudes of separate values of principal strains: within ±40 microinch/inch.
- Packaged 5 gages to the package with cement and complete instructions for installation.

LIMITATION:

- Will not perform accurately in areas of high strain gradients. (Use classical PhotoStress or miniature type MetalFilm strain gages.)

WRITE OR CALL FOR FULL INFORMATION OR APPLICATION ASSISTANCE

INSTRUMENTS Budd DIVISION

THE BUDD COMPANY • P.O. Box 245 • Phoenixville, Pa.

Consult your phone book for sales offices in: Atlanta, Ga.; Oak Park, Ill.; Detroit, Mich.; Seattle, Wash.; Dallas, Tex.; Los Angeles, Calif.

In Canada: Budd Instruments, Ltd., 170 Donway West, Don Mills, Ont.

Other countries: Budd S.A., 10 Avenue de la Grande Armée, Paris 17e, France

For details, circle No. 1 on Reader Information Card

experimental mechanics

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this month

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STRAIN GAGE INSTRUMENTS

NEW

BA-3 BAM-1 without large meter. In a case which racks 6 in an $8^3/_4$″ x 19″ panel. Or makes a neat package for individual use. Has own batteries. DC system—dc to 20,000 cps flat. Drives tape recorders and scopes directly. —$600

A-2 Output amplifier. Same case as BA-3. Own batteries. DC to 10,000 cps flat. Gain 2-20. Drives all galvos. Max. output ±60 ma into 50 ohms. Designed to be driven by BA-3, BAM-1, BAM-3. —$400

BA-3

A-2

REGULARS

BAM-1 General purpose box. Static on own meter. Dynamic with 'scope. DC bridge, dc transistor amplifier, 2 or 4 arm bridge. Battery operated. Low amplifier noise and drift. Frequency dc to 20,000 cps. Differential input cancels hum. —$525

B-1 Bridge. No amplifier. Operates off 115v 60 cycle line. 100 volts at 75 ma. max dc bridge power. 1% regulation. Line noise satisfactory on static indicators, differential input oscilloscopes and floating galvos. Not satisfactory on single sided scopes. Frequency dc to 20,000 cps. —$425

BA-12] Monitors fatigue tests. "Dynamic null balance" system gives wheatstone bridge accuracy to measurement of steady state dynamic signals including dc offset. Uses 'scope as indicator. 5 to 20,000 cps. —$650

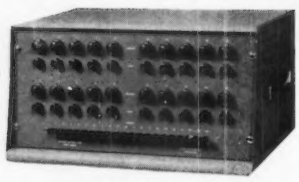
BSG-6 6 channel switch and balance. Bridge power attenuation on each channel. 1, 2 or 4 external bridge arms. Any compensating gage can be connected into one or more channels. —$350

BSG-20 20 channel switch and balance. $8^3/_4$″ x 19″ rack panel size. —$900

BAM-1

B-1

BSG-6



BSG-20

COMING

BA-13 New version of BA-12. Transistor amplifier. Frequency 1 to 20,000 cps. Variable SPREAD pot as well as fixed values. MEASURE zero at end of dial with + − switch. BAM-1 case. —around $800

BAM-3 Transducer box. Similar to BAM-1 but with minimum confusion of controls. 4 arm bridges only. Zero left meter. Definite ranges selected by switch. 'Scope connection. Frequency dc to 10,000 cps. —around $500

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experimentally Speaking

A NEW JOURNAL AND NEW IDEAS

With this first issue of EXPERIMENTAL MECHANICS, the Society for Experimental Stress Analysis is not only launching a new journal but is also formalizing a new name. For SESA has grown.

This growth has been accompanied by an increase in scope of interests. No longer can SESA be concerned solely with methods of stress analysis; its activities now carry it beyond to the broader realm of experimental mechanics.

SESA has depended primarily on volunteer help to operate the Society. As the Society has grown, there has been a corresponding increase in the burden on its officers, committee members and, particularly, on its hard-working secretary-treasurer. In recent years it has become increasingly apparent that a full-time executive secretary is required, not only to relieve volunteers but also to provide the continuity of operation necessary to insure improved and more beneficial services to members.

As one of these new services, the publication of EXPERIMENTAL MECHANICS represents a major step in the history of the Society. More papers will be published sooner and many additional features will be introduced. All members in good standing will receive the journal each month.

In formalizing the new name, our members are acknowledging the broadened scope of their activities. They are also opening the door to new contributions in this field. There are, of course, many important areas of special interest to us. However, I would like to refer briefly to one particular aspect: the experimental studies oriented towards the verification and improvement of theory.

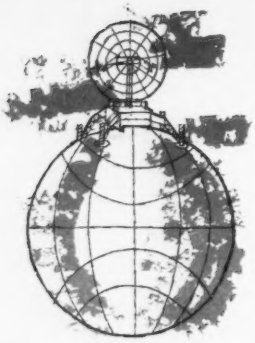
I have spent the last five months in Europe reviewing research programs in material and structural damping. One of the strongest motivations I have found among the many engineers and scientists working in this and other fields is the urge to improve current theories so that they are more compatible with engineering reality.

What is the process by which improved compatibility between theory and reality is achieved? Indications are that the most effective road to lasting progress is by a well-coordinated combination of theoretical and experimental studies.

Looking to the future, the solution of the increasingly complex engineering problems must rely more and more on experimental-mechanics studies to indicate limitations in current theories, to formulate the more realistic and general, yet simple, assumptions required for developing new theories, and later to check the compatibility of these new theories with still newer engineering situations or simulations thereof.

New thoughts and contributions in the various phases of experimental mechanics must be encouraged. The need for rapid dissemination of these new ideas is particularly acute. In its broader role, the SESA will rely on its journal to fill this need.

B. J. Lazan
SESA PRESIDENT, 1959-60



tracking station

the industry in focus

World Adopts New Standard of Length

On Oct. 14, 1960, the world adopted a new international standard of length—a wavelength of light—replacing the meter bar which has served as the standard for over seventy years. The announcement was made from Paris by Allen V. Astin, Director of the National Bureau of Standards, U. S. Department of Commerce. The action was taken by the 11th General Conference on Weights and Measures, which was meeting in Paris.

Other actions taken by the Conference included the establishment of a central facility at the International Bureau of Weights and Measures for international coordination of radiation measurements and confirmation of a new definition of the second of time. The new definition of the meter as 1,650,763.73 wavelengths of the orange-red line of krypton 86 will replace the platinum-iridium meter bar which has been kept at Paris as an international standard for length since 1889 under the Treaty of the Meter.

While not of great concern to the man in the street, these actions of the General Conference are of great importance to those engaged in precision measurement in science and industry. For many years the world has relied on a material standard of length—the distance between two engraved lines on the international meter bar kept at Paris. Duplicates of the international standard were maintained in the standards laboratories of other countries of the world. From time to time it was necessary to return these duplicates to Paris for recalibration, and occasionally discrepant results were obtained in these recalibrations. Also, there was doubt in the minds of some scientists regarding the stability of the international meter bar. The new definition of the meter relates it to a constant of nature, the wavelength of a specified kind of light, which is believed to be immutable and can be reproduced with great accuracy in any well-equipped laboratory.

ISA Elects Officers for 1960–61

Members of the Instrument Society of America at their 15th annual meeting in New York City on September 27, held in conjunction with the Society's Fall Instrument-Automation Conference & Exhibit in the New York Coliseum, elected officers for the year 1960–61. Assuming presidency of the Society, after serving a year as president-elect–secretary, was Ralph H. Tripp, Huntington, L. I., assistant director, Flight Test Division, Grumman Aircraft Engineering Corp., Bethpage, L. I., with which company he has been associated for the last 18 years.

Chosen president-elect–secretary, which moves him into position for the post of president 1961–62, was Philip A. Sprague, president of the Hays Corp., Michigan City, Ind.

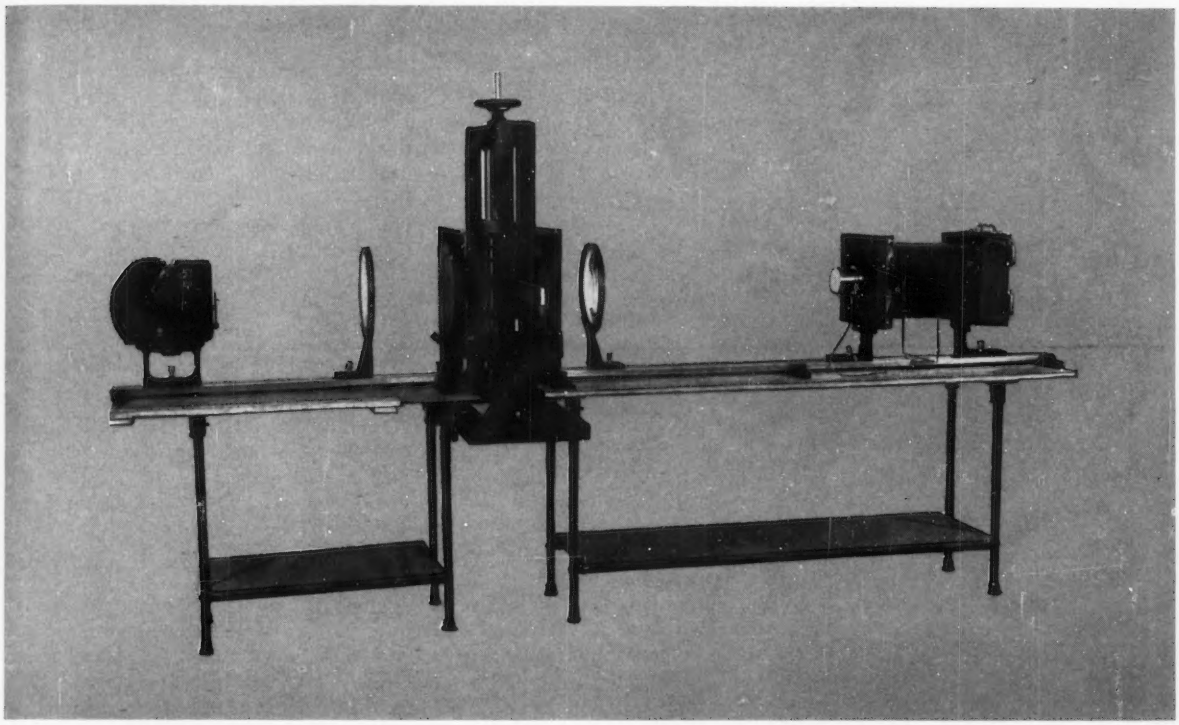
John C. Koch, Ft. Washington, Pa., executive vice-president of Conoflow Corp., Philadelphia, Pa., was elected treasurer of ISA. He has been filling this position since 1959 on an unexpired term.

Elected vice-president of ISA's Technical Department was Henry J. Noebels, Santa Ana, Calif., manager of applications engineering, Beckman Instruments, Inc., Fullerton, Calif.

E. Albert Adler, Springfield, Pa., chief instrumentation engineer, United Engineers & Constructors, Inc., Philadelphia, was elected vice-president, Standards & Practices Department.

Named as vice-president-elect, Industries Department, was John J. McDonald, vice-president and director of engineering, Consolidated Systems Corp., Monrovia. Calif.

LIGHT CONTROLS FOR PHOTOELASTIC STRESS ANALYSIS WITH POLAROID FILTERS



Photoelastic Polariscope #402
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Universal Loading Frame #421

All collimated light polariscopes have:

Point Light Source
Parallel Light Path
White Light and Monochromatic
Analyzer and Polarizer are cemented glass laminations of 6/006 Polaroid polarizing film
Matched Quarter Wave Plates
Quarter Wave Plates slide out of the optical path when not required.

Components are available

Polaroid® by Polaroid Corporation

POLARIZING INSTRUMENT COMPANY, Inc.

IRVINGTON-ON-HUDSON, NEW YORK

Almay Research Expands

Almay Research and Testing Corp. of Los Angeles has expanded its special fastener-testing facilities with the installation of cryogenic and elevated-temperature test chambers, according to an announcement by its president, Harry S. Brenner.

The new extreme temperature equipment permits testing of bolts, screws, nuts, rivets and similar type fasteners through a temperature range down to −320° F and as high as 2000° F. The environmental testing is being carried out to determine strength requirements of fasteners used in new-type airframes, missiles and power plants.

Almay's new cryogenic test chamber, permitting testing at subzero temperatures, is cooled through two separate systems utilizing liquid carbon dioxide to a level of −100° F, and liquid nitrogen to −320° F. The chamber has a 4-cu ft working space specifically designed to accommodate an extensometer which records stress-strain test data on the fasteners being tested under low-temperature conditions.

At the other extreme, Almay utilizes a split-type electric furnace with an extensometer for its high-temperature testing to 2000° F. Both pieces of equipment are capable of simulating loads up to 120,000 lb on fasteners.

Mr. Brenner is a member of the SESA.

Weidemann Markets Physical Testing-machine Line

As originally announced a few months ago, the testing-machine product line of the Electronics and Instrumentation Division of Baldwin-Lima-Hamilton Corp. has been transferred to the Wiedemann Machine Co., Gulph and Long Roads, King of Prussia, Pa. This transfer has covered the physical testing-machine business only and has not included the Baldwin SR-4 strain gages, transducers and associated instrumentation. These products continue to be marketed and manufactured on an expanded basis by the Electronics and Instrumentation Division of BLH at Waltham, Mass.

Wiedemann Machine Co. is proceeding with the testing-machine business using the services of all key sales, engineering and service personnel associated with BLH's testing-machine activity at the time of the transfer. Wiedemann has also acquired BLH patents, drawings, spare parts inventory and calibration equipment. The testing machines will continue to be marketed under the Baldwin trade name.

FUTURE MEETINGS

SESA

MAY 10–12. Spring Meeting. Benjamin Franklin Hotel, Philadelphia, Pa.

NOVEMBER 1–3. International Congress on Experimental Mechanics. Hotel New Yorker, New York, N. Y.

AAS

JANUARY 16–18. Annual Meeting of American Astronautical Society. Sheraton Hotel, Dallas, Tex.

ARS

FEBRUARY 1–3. Solid Rocket Propellant Conference of the American Rocket Society. Hotel Utah, Salt Lake City, Utah.

APRIL 5–7. Conference. Lifting Re-entry Vehicles: Structures, Materials, Design. Palm Springs, Calif.

ASTM

JUNE 25–30. Annual Meeting of American Society for Testing Materials. Chalfonte-Haddon Hall, Atlantic City, N. J.

IAS

JANUARY 23–25. Annual Meeting of the Institute of the Aerospace Sciences. Hotel Astor, New York, N. Y.

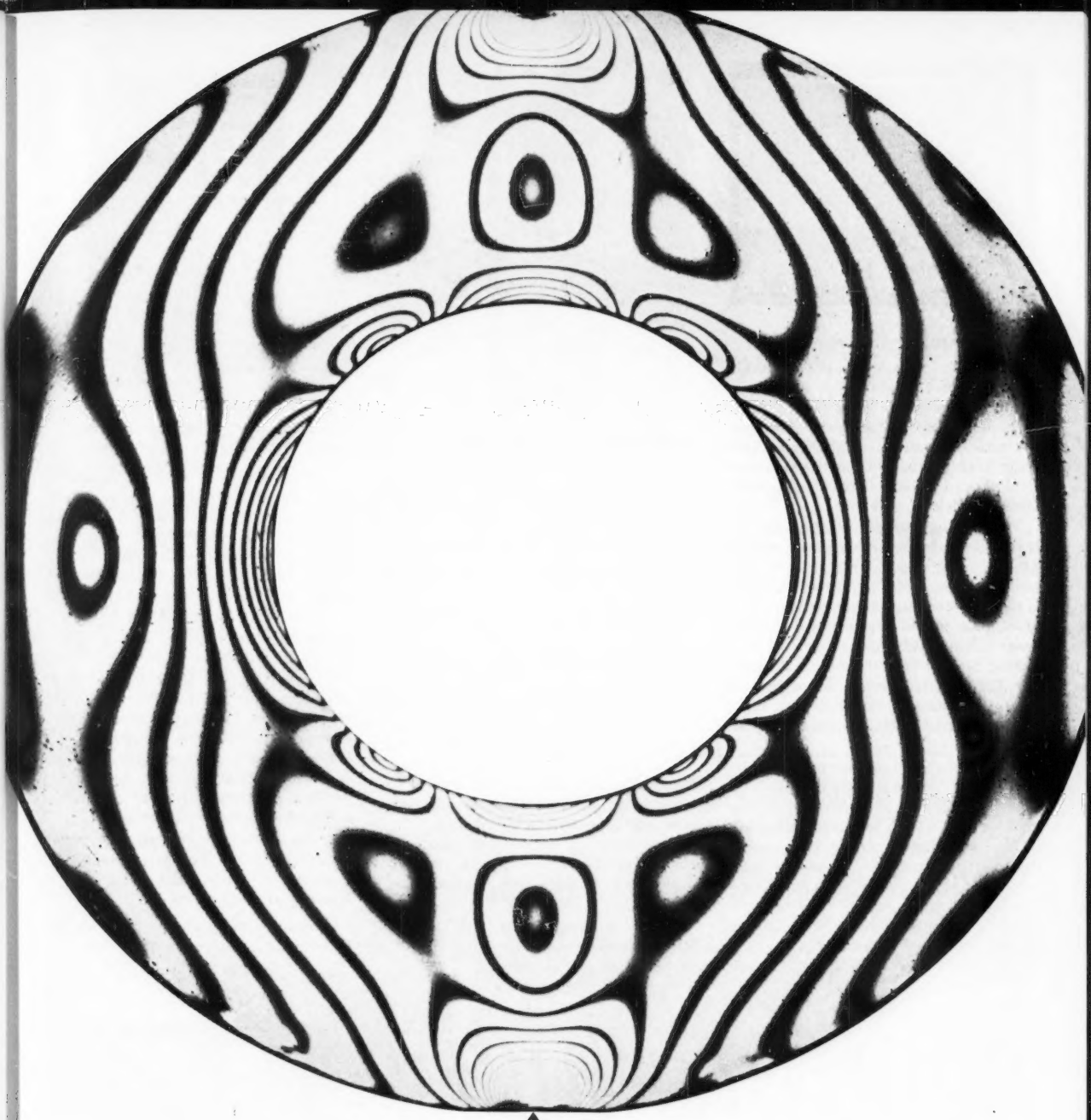
ISA

APRIL 17–19. Symposium on Instrumental Methods of Analysis. Instrument Society of America. Shamrock Hilton Hotel, Houston, Tex.

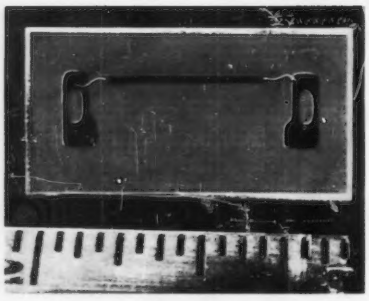
SAE

JANUARY 9–13. Annual Meeting of Society of Automotive Engineers. Cobo Hall, Detroit, Mich.

For details, circle No. 4 on Reader Information Card→



For information on polarizers for stress analysis write Polaroid Corporation, Cambridge 39, Mass.



SEMICONDUCTOR STRAIN GAGE

Production quantities of bondable semiconductor strain gages for microstrain measurement in all types of military, space and industrial applications are now available through Micro Systems, Inc., a subsidiary of Electro-Optical Systems, Inc., 2925 E. Foothill Blvd., Pasadena, Calif.

According to the manufacturer, this strain-detection device, called Micro-Sensor, Model MS 105-350, is bondable to practically all surfaces, and is especially applicable to measurement of minute strain imposed upon small areas. Sensitivity of the device is reported to be 50 to 60 times that of its metallic counterparts. Additionally, its low impedance, coupled with high output, results in high signal-to-noise ratio.

Micro-Sensor measures 1 in. in length and $^1/_2$ in. in width. It consists of a thin silicon element, $^5/_8$ in. long, 0.020 in. wide and 0.0005 in. thick, attached to an epoxy based carrier for application to test surfaces. Integral lead tabs are provided for connection to instrumentation systems.

For details, circle No. 51 on Reader Information Card.

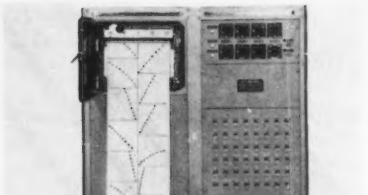
LOAD-SPECTRUM PROGRAMMER

A new automatic-test load-spectrum programmer has been developed by Research, Inc., P. O. Box 6164, Minneapolis 24, Minn.

The manufacturer states that, instead of repeatedly resetting his load-cycling equipment for each band of the load spectrum as in a normal fatigue-test procedure, the engineer using this programmer merely charts (on separate sheets of graph paper) the amplitude and frequency of load cycles for one complete spectrum. He then attaches these program charts to two rotating drums in the instrument, sets a "count-down" type counter at the total number of cycles or the total number of spectrum repetitions desired and presses a starting switch.

Two function generators "reading" the pencil-drawn charts, guide the programmer through the entire test spectrum.

For details, circle No. 52 on Reader Information Card.



MULTICHANNEL STRAIN-GAGE PLOTTERS

A new line of Model 114 strain-gage plotters, available for immediate delivery from stock—instead of being custom built—has just been announced by Gilmore Industries, Inc., 13015 Woodland Ave., Cleveland 20, Ohio.

The Gilmore Model 114 is a multichannel recording and plotting instrument for strain-gage use, available with 48 or 96 channels. It requires no manual plotting or reading, automatically records data in visual form for "on-the-spot" evaluations. Other features include 3 zero positions per channel, individual graphs for each channel, individual channel lights and a portable motor-driven zero balance gun.

According to the manufacturer, with the M114, structural design engineers get required data while a test is in actual progress.

For details, circle No. 54 on Reader Information Card.

new products

RESISTANCE STRAIN GAGE

Statham Instruments, Inc., 12401 W. Olympic Blvd., Los Angeles 64, Calif., has introduced a versatile resistance strain gage, Model SG2, with a complementing portable bridge control readout, Model BCR1-0.

It is reported that Model SG2 resistance strain gage is designed for repetitive measurement of strain or unit elongation, with applications in aircraft-test certification, structural-steel-column loading, concrete-specimen studies, etc. It incorporates the Statham zero-length unbonded strain gage, and has strain or elongation sensed between two fixed knife edges and one movable knife edge. This instrument is said to be particularly useful in preliminary investigations to locate critical areas warranting further study.

For added SG2 versatility, Statham's BCR1-0 bridge-control readout provides a combined power supply, bridge balance and electrical readout meter.

For details, circle No. 53 on Reader Information Card.

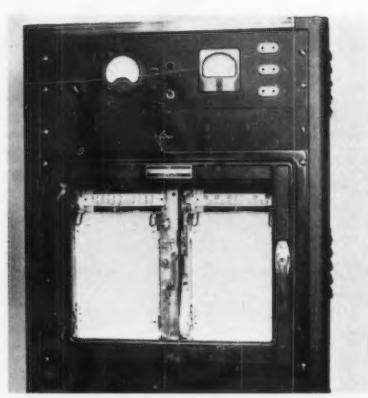


CHART DRIVE FOR TWIN RECORDERS

The Esterline-Angus Co., P. O. Box 596, Indianapolis 6, Ind., announces the introduction of a new high-speed chart drive for use in its twin recorders. This drive, which is housed entirely within the recorder case, has

been designed as an alternate to the Esterline-Angus high chart-speed attachment which is mounted on the outside of the recorder. The new drive will prove particularly useful where E-A twin recorders are to be installed in relay racks; it eliminates the rack modification made necessary by the external drive. This new drive provides speeds as high as three inches per second, and can be shifted electrically from hour to minute to second speeds, and vice versa.

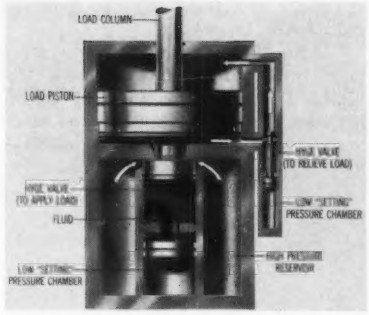
The E-A Co. also announces that it now manufactures twin recorders designed specifically for flush mounting in 19-in. relay racks.

For details, circle No. 55 on Reader Information Card.

DYNAMIC-LOADING INSTRUMENT

The development of a special dynamic-loading instrument has been announced by Convair Dynapak, Convair Division, General Dynamics Corp., 435 W. Fifth St., Pomona, Calif. The device is described as being capable of applying millions of pounds of force in a fraction of a second, duplicating in the laboratory actual in-use environments.

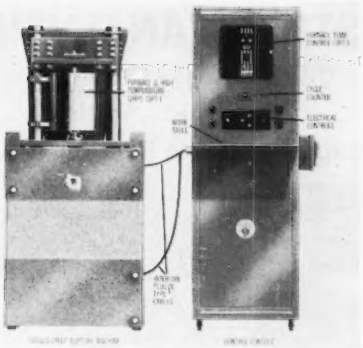
The Dynapak unit incorporates the Hyge principle for duplicating



shocks caused by sudden accelerations and decelerations. Unlike Hyge shock testers, however, the dynamic-loading instrument involves no significant motion. Instead, the test specimen is bolted to an apparatus that is similar, in many respects, to a compression testing machine. A button is pushed, and within one-thousandth of a second, the full test load is applied.

The load is maintained for any desired length of time up to a minute or more, then relieved in less than twenty milliseconds. The load level, rise time, dwell time and decay time may be controlled externally.

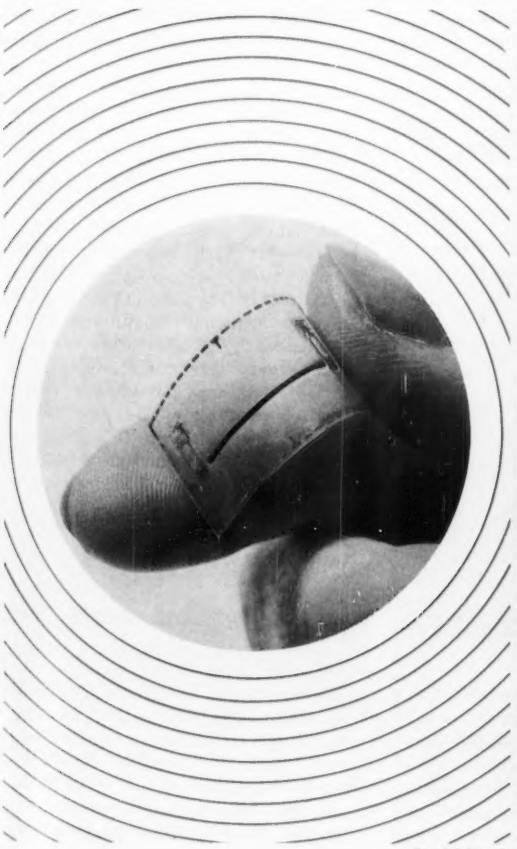
For details, circle No. 56 on Reader Information Card.



UNIVERSAL FATIGUE MACHINE

A new Tatnall-Krouse universal testing machine for combination fatigue testing was put on the market recently by the Instruments Division of the Budd Co., Box 245, Phoenixville, Pa.

Highlights of this machine, which has been labeled as Model LAZ-1, are reported to be its ruggedness—it is stressed to withstand the most punishing testing programs; its compactness—test machine measures $29^1/_4$ x $27^1/_2$ x 67 in. high, control rack 22 x 17 x 70 in. high; and its versatility. The machine provides for static or dynamic testing on a selective basis; creep or fatigue work may be accomplished with



MICRO-STRESS INSTRUMENTATION
Orders of Magnitude More Sensitive
SEMICONDUCTOR STRAIN GAGE
MICRO-SENSOR MS 105-350
For Application to: Structural Members • Transducer Sensors
FEATURING
- Sensitivity—gage factor 130
- Easily bonded to all types of surfaces for military, industrial, and space applications
- Integral terminal construction
- Superior signal-to-noise ratio
- Resistance—350
- Size: Element—⅝" x .020" Complete Gage—1" x ½"
- Radius of Curvature—½"
- Maximum Operating Strain—over 3000 microstrain

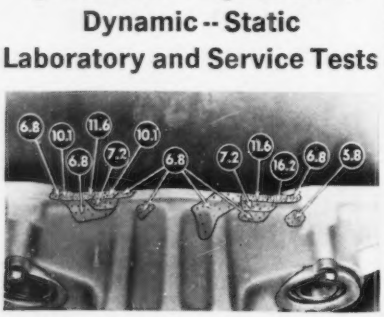
IMMEDIATELY AVAILABLE—
ADDITIONAL INFORMATION ON REQUEST

MS
MICRO SYSTEMS INCORPORATED
[illegible] Agoura Rd., San Gabriel, California
A Subsidiary of Electro-Optical Systems Inc.

For details, circle No. 5 on Reader Information Card

Quick -- Reliable STRESS ANALYSIS

Quantitative -- Qualitative
Dynamic -- Static
Laboratory and Service Tests



STRESSCOAT®

Stresscoat spray-on brittle coating stress analysis shows distribution, direction and stress level in simple or complex shapes over the entire part. Sharply defined stress indications on the part itself make evaluation with any of numerous coatings quick and positive. New ceramic All-Temp Stresscoat can be used on parts immersed in oil or tested at temperatures to 600° F. Used by leading laboratories and manufacturers to reduce costs, build better, stronger products that weigh less.

COMPLETE LOW-COST KITS – READY TO USE

AFTER ANALYSIS—TEST
As a stress engineer you must depend upon the integrity of materials and parts in relation to stress levels. After evaluation, suggest areas where cracks or laps are most serious. One or another of these Magnaflux Test Systems can help you assure the serviceability of your designs.

MAGNATEST®
Nondestructive electronic eddy current testing instruments for cracks, seams, coating thickness, alloy, etc.

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Fluorescent penetrant marks cracks or pores in nonmagnetic materials.

MAGNAFLUX MATERIALS TESTING SERVICE
From 15 principal cities. Let us test your pilot runs for cracks or suspected cracks due to fatigue in service units. Write for details.

MAGNAFLUX CORPORATION
Subsidiary of General Mills
7356 West Lawrence Avenue
Chicago 31, Illinois

For details, circle No. 6 on Reader Information Card

either of the machine's two sections: the static unit (LAZ-1S), the dynamic unit (LAZ-1D) or both.

Also, the static and dynamic units may be readily removed from the LAZ-1 and assembled in combination for direct use on structures too large or complex to be tested in the machine itself.

For details, circle No. 57 on Reader Information Card.

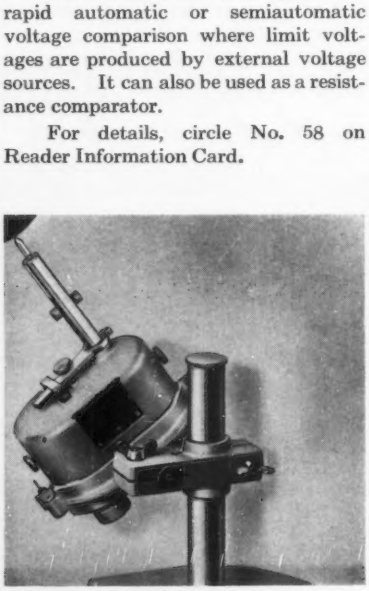
VOLTAGE-COMPARISON AMPLIFIER

A new transistorized voltage-comparison amplifier with a highly favorable combination of sensitivity, range and input impedance has been announced by Non-Linear Systems, Inc., Del Mar, Calif., for a broad range of critical go/no-go application.

According to manufacturer, Model 51 provides a precise, fast and reliable way to determine if an input voltage or series of input voltages is within preset limits. It does this by means of colored bulbs which light for visual indication and relays to operate external warning and control devices. Both indications occur within 90 millisec after applying the voltage under test.

The instrument is designed for rapid automatic or semiautomatic voltage comparison where limit voltages are produced by external voltage sources. It can also be used as a resistance comparator.

For details, circle No. 58 on Reader Information Card.



HAND VIBROGRAPH

Epic, Inc., 154 Nassau St., New York 38, N. Y., announces the availability of the Askania "hand vibrograph." This unit is described as a compact and light ($3^3/_4$ lb) instrument suitable for measuring mechanical vibrations on machinery, airplanes, ships and vehicles, as well as on component parts such as shafts, springs, etc. It is built for a frequency range from 0 up to 250 cps for accelerations up to 50 g. It is driven by its own clockwork, and its time markers are operated by a built-in 6-v battery. It uses no ink and records by stylus on a waxed-paper tape. The amplitude range is from 0.0001 in. up to $^3/_8$ in.

It is reported, in addition, that the instrument can also be used to measure torsional vibrations on shafts, and even pressure vibrations on liquid or gas-carrying pipes.

For details, circle No. 59 on Reader Information Card.

DUCTILITY-TESTING MACHINE

A new type of ductility-testing machine designed for foil and thin-sheet work is now available from Detroit Testing Machine Co., 9390 Grinnell Ave., Detroit 13, Mich. Called thin sheet metal and foil tester (Model TSD), the machine is designed to permit quick, accurate readings for both experimental and production work, according to the manufacturer. Gripping pressure and movement of test piston of the machine may be adjusted to different levels independently of each other, so as to fit whatever test conditions are desired. Tests are carried out in full view of operator. The new testing machine is available in five gage calibrations, ranging from 200 to 2000 lb., for work ranging from 0.002 to 0.020 in. maximum thickness.

For details, circle No. 60 on Reader Information Card.

ABSOLUTE PRESSURE TRANSDUCER

The availability of a microminiature, flush diaphragm absolute pressure transducer that is drastically reduced in size and weight has been announced by Statham Instruments, Inc., 12401 W. Olympic Blvd., Los Angeles 64, Calif.

This new pressure transducer is "smaller than a dime" and was de-

signed for airborne, missile and wind tunnel applications where small size and light weight are critical. The micro-miniature transducer features a flush diaphragm with high frequency response; ranges are 0–10 psia to 0–100 psia; and size is 0.590 in. diam by 0.050 in. thick.

For details, circle No. 61 on Reader Information Card.

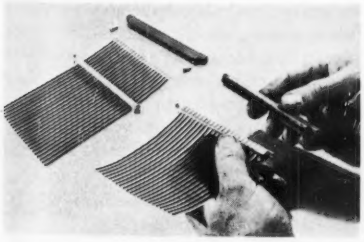
VARIABLE-PHASE STANDARD

Gertsch Products, Inc., 3211 S. La Cienega Blvd., Los Angeles 16, Calif., announces a variable-phase standard which permits phase between two self-generated voltages to be shifted to any desired angle, with an accuracy of ±0.05 deg or better.

The manufacturer states that the instrument generates two signals of equal amplitude, differing in phase by any angle from 0 to 360 deg, as determined by front-panel controls. The reference signal has a fixed amplitude of 50V rms. Vector output, which may be displaced in phase, has a maximum amplitude of 50V rms, and can be attenuated in steps of 50 mv within the range of 0–50V rms. A front-panel selector switch permits operation at any of three frequencies within the range of 150 to 3000 cps, variable ±5% max.

Designated as Model VPS-1, unit is completely self-contained, requiring no external equipment for operation or calibration.

For details, circle No. 62 on Reader Information Card.



CONTOUR CABLE AND CONNECTING DEVICES

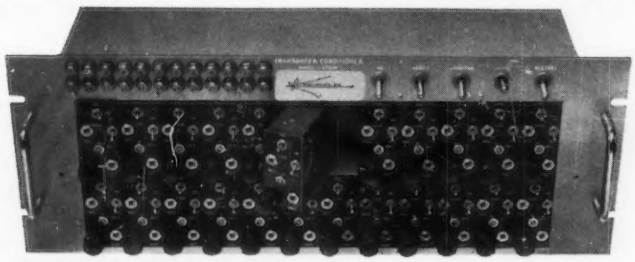
Two types of weight- and space-saving multiconductor cable, only 0.012 in. thick, and a variety of connecting devices are now being marketed commercially by Hughes Aircraft Co., Industrial Systems Divisions, International Airport Station, P. O. Box 90904, Los Angeles 45, Calif.

The flexible flat cable, called contour cable, is produced in a number of material combinations to meet any range of temperatures from −65° to +250° C, the company states.

As many as 54 conductors per inch can be assembled in a single cable for micro-miniaturization application.

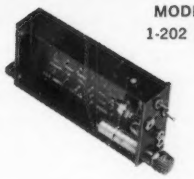
For details, circle No. 63 on Reader Information Card.

A DATA ACQUISITION SPACE SAVER . . . the B & F subminiature modular strain gage and transducer input conditioner. Now, B & F offers individual plug-in bridge balancing and calibration printed circuit modules. Series or shunt calibration via the "6-wire" technique . . . manual or automatic, simultaneous or sequential. Any number of channels packaged as required.



19" x 7" rack adapter houses 24 channels

MODEL 1-202 AM

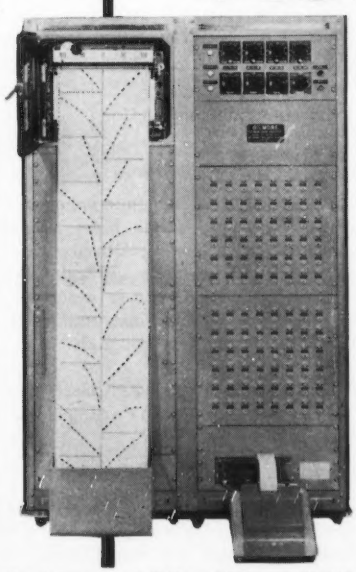


B & F instruments, Inc.
3644 N. Lawrence St.
Philadelphia 40, Pa.

Torque Meter Systems, Accelerometers and other equipment for data acquisition.
For details, circle No. 7 on Reader Information Card

PLOT DATA "On-The-Spot"

Strain Gage, Thermocouple, or Millivolt Input



The Gilmore Model 114 Autographic Plotter is a multi-channel recording and plotting instrument for use with strain gage, thermocouple, or millivolt inputs. It automatically receives and plots each channel on an individual graph so that test personnel can quickly evaluate results, "on-the-spot", while the test is actually in progress.

Gilmore Plotters reduce reruns—help eliminate faulty test setups and overloaded test specimens. Installations save time, engineering, and technical manpower.

Model 114 Autographic Plotter is available in 24, 48, or 96 channel models. A digital converter can be driven simultaneously with the plotting to operate a tape punch, card punch, electric typewriter, or printer.

Write Dept. 0

Manufacturers of: Multi-Channel Plotters • Weighing Systems • Thrust and Force Measuring Systems • Strain Gage Instrumentation • Digital Indicating Potentiometers • Data Loggers

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For details, circle No. 8 on Reader Information Card

Semiconductor Gages

The availability of new types of strain gages which are said to provide all the desirable characteristics of conventional strain gages, but which are more versatile and provide significantly higher outputs, is announced by Kulite-Bytrex Corporation, 50 Hunt Street, Newton 58, Massachusetts.

According to the manufacturer, Kulite semiconductor gages have such large output that they can be used to drive panel meters and relays directly without amplifiers. This makes possible simple, highly reliable, inexpensive systems for monitoring and control.

In addition to their large output, the gages are reported to lend themselves very well to the measurement of high-frequency phenomena. A four-arm semiconductor strain-gage bridge will provide outputs in the order of 100 millivolts at total deflections of 50 millionths of an inch. This provides natural frequencies in excess of 100 kilocycles.

Kulite-Bytrex also announces that the company has made commercially available, for the first time, strain gages with negative gage factors and, in addition, MP series gages. The latter are dual-element temperature-compensated gages corrected for "apparent strain" on specific materials.

Gage characteristics are described in detail in Bulletin K-101.

For your free copy, circle No. 101 on Reader Information Card.

Instrumentation

Statham Instruments, Inc., 12401 W. Olympic Blvd., Los Angeles 64, Calif. has published a fully illustrated, 32-page general catalog with concise descriptions of Statham pressure transducers, linear and angular accelerometers, load cells, amplifiers, power supplies, bridge balances, strain gages and force/displacement transducers.

To facilitate instrument selection for specific user requirements, the Statham catalog contains easy-to-read selection charts keyed to instrument ranges. Tables of conversion factors for pressure, force, linear acceleration, temperature, angular velocity, plane angles and weight are included for quick reference.

For your free copy, circle No. 102 on Reader Information Card.

Strain Gages

H. Tinsley & Co. Ltd., Werndee Hall, South Norwood, London, S.E. 25, announces the availability of four pamphlets on strain gages: List 210, "Electrical Wire Resistance Strain Gauges"; List 210G, "'A' Range Medium Temperature Strain Gauges"; List 210H, "High Resistance Foil Gauges"; and List 210J, "'B' Range High Temperature Strain Gauges."

For your free copy, circle No. 103 on Reader Information Card.

400 CPS Choppers

Bulletin C-33, describing Series 300 choppers for 400 cycle operation, is available from Airpax Electronics, Inc., Cambridge Division, Cambridge, Md. The bulletin includes discussions of contact capacity, life, dwell time, phase angle and noise. A phase-shift network to produce zero-phase operation and internal chopper construction are illustrated.

A summary of chopper ratings including electrical characteristics, environmental conditions and mechanical characteristics and a glossary of chopper terms and definitions are detailed in Bulletin C-33.

For your free copy, circle No. 104 on Reader Information Card.

Testing Instruments

An illustrated, four-page pamphlet, No. P-560, has been released recently by Thwing-Albert Instrument Co., Penn St. at Pulaski Ave., Philadelphia 44, Pa. It describes a number of testing instruments for paper, plastic, textiles, light metals and other materials.

For your free copy, circle No. 105 on Reader Information Card.

Industrial Instruments

A special applications section is featured in the new 12-page, two-color bulletin offered by Non-Linear Systems, Inc., Del Mar, Calif., on its industrial series digital measuring instruments. The section covers 17 uses of the NLS 481 digital voltmeter and the NLS 781 digital ohmmeter with individual photos and descriptive material.

The booklet also includes a 2-page color spread on 481 digital voltmeter features, comparisons of the 481 digital voltmeter features, comparisons of the 481 with pointer meters and other dry stepping switch instruments, standard 481 modifications with wiring diagrams, conversion to a-c and low-level d-c measurements, complete specifications on both instruments and operation information.

For your free copy, circle No. 106 on Reader Information Card.

Accelerometers and Amplifiers

The following short-form sheets are available from Columbia Research Laboratories, Inc., MacDade Blvd. and Bullens Lane, Woodlyn, Pa.: T-102, "Electronic Instrumentation for Laboratory and Field Installations"; T-103, "Transistorized Amplifiers for Airborne Applications"; and T-104, "Accelerometers."

For your free copy, circle No. 107 on Reader Information Card.

Testing Machines

Riehle Testing Machines, Division of American Machine and Metals, Inc., East Moline Ill., announces the availability of a new bulletin describing the company's measuring components and complete systems for force and distance. This bulletin is fully illustrated with photographs and schematic drawings.

For your free copy, circle No. 108 on Reader Information Card.

Instrumentation Systems

A condensed catalog describing instruments for measurement of temperature, pressure, level and flow has just been published by Trans-Sonics, Inc., P. O. Box 328, Lexington 73, Mass.

This catalog is in the convenient pocket size (5 x 7 in.) and consists of eight pages printed in two colors.

Features and application information are given for a variety of instruments including: pressure potentiometers, an ultra-sensitive low-pressure measurement system, a wide-range electronic micromanometer, temperature transducers for surface, liquid and gas temperature-measuring systems, temperature standards, liquid-detection systems and mass-flow systems.

For your free copy, circle No. 109 on Reader Information Card.

All-electronic Digital Voltmeter

A two-color, six-page bulletin on the new high-accuracy, V44, all-

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In the space age, measurements of stresses, forces and accelerations must be made to check calculations and to obtain information that cannot be calculated.

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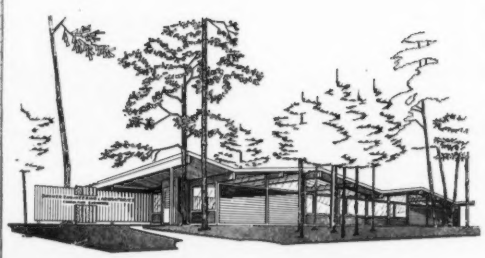

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Wiley BOOKS

THEORY OF THERMAL STRESSES
By B. A. Boley *and* J. H. Weiner, *both of Columbia Univ.* Unites thermodynamical foundations and practical material of interest to engineers and researchers. *1960. 586 pages. $15.50*

NATURE AND PROPERTIES OF ENGINEERING MATERIALS
By Z. D. Jastrzebski, *Lafayette College.* Much more basic than the usual treatment, this stresses materials from an engineering viewpoint, with realistic, practical applications. *1959. 571 pages. $11.00*

RADIATION PYROMETRY AND ITS UNDERLYING PRINCIPLES OF RADIANT HEAT TRANSFER
By T. R. Harrison, *Minneapolis-Honeywell, Brown Instruments Div.* Covers three major areas: theory, principles; details of construction and operation of instruments. *1960. 234 pages. $12.00*

INTRODUCTION TO CERAMICS
By W. D. Kingery, *M.I.T.* Considers ceramics as a *class* of materials rather than specialized products. Stresses properties from the viewpoint of understanding characteristics and applications. *1960. Approx. 704 pages. $15.00*

ELECTRONIC PROCESSES IN SOLIDS
By P. Aigrain, *Univ. of Paris;* R. J. Coelho, *Ingenieur des Arts et Manufactures;* and G. Ascarelli, *Laurea in Fisica.* Covers band theory and transport theory in covalent semiconductors. Includes a new thermodynamic approach. A Technology Press Research Monograph, M.I.T. *1960. 67 pages. $4.00*

PROPERTIES AND STRUCTURE OF POLYMERS
By A. V. Tobolsky, *Princeton Univ.* Reduces seemingly complex physical properties to easily grasped fundamentals. Shows how mechanical behavior can be used to solve problems in polymer chemistry, often otherwise unsolvable. *1960. 331 pages. $14.50.*

NON-CRYSTALLINE SOLIDS
Edited by V. D. Frechette, *State Univ. of New York.* Record of a conference on defining and identifying amorphous structures, assessing methods of research and results. *1960. 536 pages. $15.00*

CRYSTAL-STRUCTURE ANALYSIS
By M. J. Buerger, *M.I.T.* Concerned with the entire field, it covers all phases of data gathering and ways of treating this material to determine arrangements of atoms. *1960. 668 pages. $18.50*

Wiley is the publisher of Hetenyi's HANDBOOK OF EXPERIMENTAL STRESS ANALYSIS. *1950. 1077 pages. $17.00*

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JOHN WILEY & SONS, Inc.
440 PARK AVENUE SOUTH, NEW YORK 16, N. Y.

For details, circle No. 10 on Reader Information Card

electronic digital voltmeter is being offered by Non-Linear Systems, Inc., Del Mar, Calif.

The folder tells how the NLS V44 can be used for high-speed measuring and data-logging applications that require maximum accuracy, reliability and stability.

Sections include the V44's special features; drawings and technical information on digital output data; specifications; applications and operating information.

For your free copy, circle No. 110 on Reader Information Card.

Mechanical Differential

A data sheet released by Ford Instrument Co., Division of Sperry Rand Corp., 31-10 Thomson Ave., Long Island City 1, N. Y., illustrates and describes the $^{3}/_{32}$-in. standard differential. This unit is the latest and smallest addition to the company's line of single spider-gear differentials.

For your free copy, circle No. 111 on Reader Information Card.

Digital Voltmeters

"Pocket Guide to the Proper Selection of Digital Measuring Instruments," a 10-page folder on factors to be considered in purchasing a digital voltmeter, is available without charge from Non-Linear Systems, Inc., Del Mar, Calif.

The guide answers such questions as: "What are the practical applications of digital measuring instruments? How important is servicing in selecting a digital voltmeter? Are digital voltmeters high priced?"

Second portion of the two-color folder covers brief specs, features and applications of instruments in the NLS line.

For your free copy, circle No. 112 on Reader Information Card.

Force and Pressure Transducers

Condensed catalog No. 294, covering "Micro-Ducer" force, pressure and strain transducers, is available from Clark Electronic Laboratories, Box 165, Palm Springs, Calif.

For your free copy, circle No. 113 on Reader Information Card.

Transistorized Amplifiers

Technical bulletin T-103, just published by Columbia Research Laboratories, MacDade Blvd. & Bullens Lane, Woodlyn, Pa., describes the company's line of miniature, solid-state amplifiers for use with piezoelectric accelerometers in missile and airborne shock and vibration studies.

The bulletin illustrates and describes twelve different models which include emitter-follower amplifiers, wide-temperature amplifiers, high-gain accelerometer-amplifiers and self-amplifying accelerometer systems.

Complete data are given on specifications such as gain, stability, linearity, frequency response, noise levels, characteristics of input and output signals and environmental performance.

For your free copy, circle No. 114 on Reader Information Card.

Humidity Effects on Microbalances

The office of Technical Information, National Bureau of Standards, U. S. Department of Commerce, Washington 25, D. C., has released Summary Technical Report STR-2525, dealing with humidity effects on microbalances.

Research at the National Bureau of Standards has shown that the rest point of microchemical balances may be seriously altered by changes in relative humidity. Errors may result from absorption of moisture by balance components and surface dirt, and unequal adsorption on opposite sides of the beam. The effect can be minimized by careful design and construction of balance mechanisms, and removal of collected foreign material.

For your free copy, circle No. 115 on Reader Information Card.

Solid-state Displacement Transducers

A data sheet on solid-state displacement transducers can be obtained from G. C. Collins Corp., 2820 E. Hullett St., Long Beach 5, Calif.

For your free copy, circle No. 116 on Reader Information Card.

Digital Voltmeter

A two-color, four-page bulletin on the new NLS 484 industrial digital voltmeter is being offered by Non-Linear Systems, Inc., Del Mar, Calif.

The bulletin explains how the 484 unit can be used with plug-in accessories to build low-cost, reliable and highly accurate measuring and data-logging systems.

Features of the 484 are covered as well as detailed technical information, specifications and operations.

The bulletin includes a chart showing some of the input and output accessories that can be used with the 484 in building low-cost measuring, testing and data-logging systems.

For your free copy, circle No. 117 on Reader Information Card.

Universal Connector Line

Universal electronic and electric connectors designed for solderless installation are now available from Hughes Aircraft Co., Industrial Systems Division, P. O. Box 90904 Airport Station, Los Angeles 45, Calif.

Typical of new devices are MS type connectors employing removable pins and sockets. Various standard configurations of basic connectors, pins and sockets are available to accommodate wire gages No. 8 through No. 22 and, also, coax cables. Custom-made arrangements of various pins and sockets are available upon special request, the division announces.

For your free copy, circle No. 118 on Reader Information Card.

GP Corporate Booklet

A multicolor, profusely illustrated, 24-page booklet has been released recently by General Precision, Inc., 92 Gold St., New York 38, N. Y. It constitutes a presentation of the facilities and capabilities of the organization.

For your free copy, circle No. 119 on Reader Information Card.

Instruments and Systems

A short-form catalog, covering information on digital instruments and systems, d-c amplifiers, *X-Y* records, and high-speed scanning, data-processing and data-logging systems, is available from Electro Instruments, Inc., 3540 Aero Court, San Diego 11, Calif.

For your free copy, circle No. 120 on Reader Information Card.

AUTHORS . . . A REMINDER . . .

The deadline for abstracts of papers proposed for the 1961 International Congress on Experimental Mechanics, Nov. 1–3, New York City, is Jan. 31, 1961. Completed papers must be submitted prior to May 31. Manuscripts should be sent to: Dr. Roscoe Guernsey, Jr., Chairman Papers and Proceedings Committee, Society for Experimental Stress Analysis, General Engineering Laboratory, General Electric Company, Schenectady 5, New York.

Sources of information on

STRAIN GAGES

STRAIN GAGE TECHNIQUES

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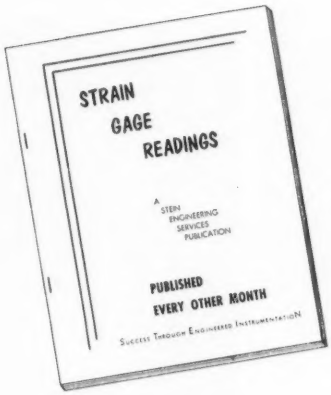
A comprehensive reference book on basic theory and experiments

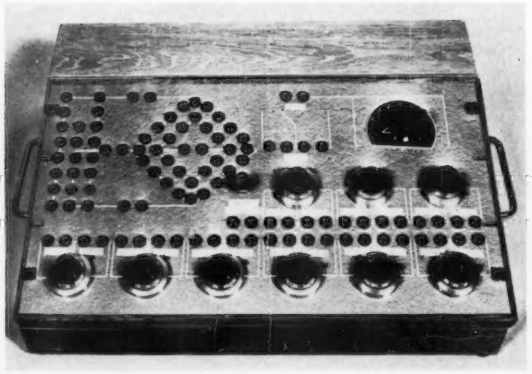
669 pages, 8½ x 11, cloth bound, photo-offset from typewritten copy



STRAIN GAGE READINGS

P. K. Stein, Editor

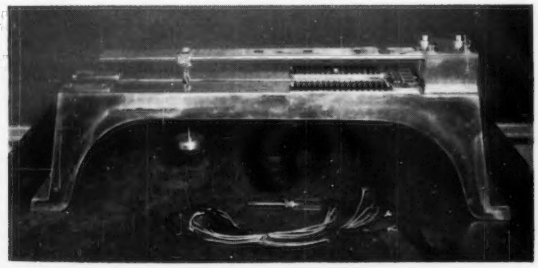
A bi-monthly journal devoted to new applications and techniques and reviews of current literature



Plug board for strain gage & instrumentation circuits

THE STRAIN GAGE INSTRUCTOR

Aluminum stand and cantilever beam with mounted strain gages



EXPERIMENTAL EQUIPMENT

for demonstrating the theory and performing the laboratory experiments which are described in STRAIN GAGE TECHNIQUES and STRAIN GAGE READINGS

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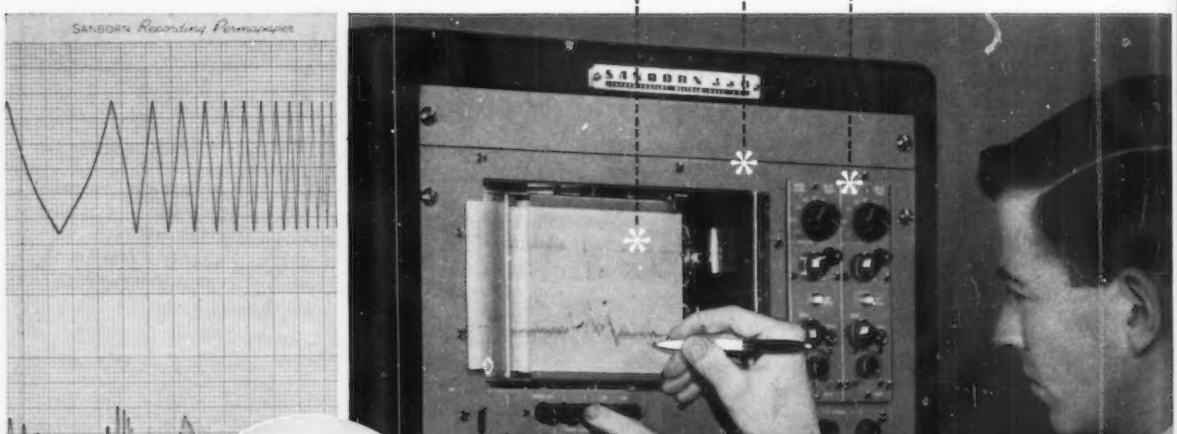
THIS NEW 2-CHANNEL DIRECT WRITER...

* *has easily read 50 mm wide, rectangular coordinate channels*

* *mounts in 10½" of rack space or in a separate portable case*

* *interchangeable "850" Series plug-in preamplifiers for each channel*



SANBORN Model 297 Oscillographic Recorder

Compactness and versatility without loss in performance is the design concept for this new 2-Channel Direct-Writer from Sanborn. The Model 297 provides two *complete* recording channels in only 10½" of panel space, making it extremely useful as a monitoring recorder — integrated with large instrumentation setups in data processing installations, test stands and similar applications. In its own portable case, the Model 297 will be equally useful in *laboratories and field applications* as a bench-top instrument.

Preamplifiers are "850" Series plug-in interchangeable units, available in Carrier, DC Coupling, Phase Sensitive Demodulator, and Low Level types. They may be used in any combination, one for each channel. An internal MOPA for carrier and chopper excitation is also available.

The basic recorder assembly houses a preamplifier power supply, transistorized power-amplifier power supply, and two transistorized current-feedback power amplifiers with *built-in electrical limiters* that provide damping at all times. The entire unit has built-in forced filtered air cooling.

The recording mechanism has rugged, enclosed galvanometers with velocity feedback damping . . . 4 different chart speeds selected by push buttons . . . timer/marker stylus with 1 second timer . . . approximately 6 inches of visible chart with immediately visible traces made by heated stylus. The electrical and mechanical specifications in combination with the many "big system" operating features make the compact Model 297 one of the most useful, reliable 2-channel direct writers available.

Contact the Sanborn Sales-Engineering representative nearest you or write the main office in Waltham for complete information and application assistance. Sales-Engineering representatives are located in principal cities throughout the United States, Canada and foreign countries.

Model 297 2-Channel Recording System Specifications
(Less plug-in preamps)

Sensitivity: 0.1 volt/mm nominal
Frequency Response: DC to 125 cps within 3 db, 10 mm peak-to-peak amplitude
Gain Stability: Better than ½% from 20°C to 40°C or line voltage change from 103 to 127 volts
Linearity: Max. non-linearity is 0.2 mm
Electrical Limiting: Approximately ±115% of full scale
Chart Speeds: 1, 5, 20, and 100 mm/sec. by mechanical push button
Dimensions: 10½" high x 16" deep x 19" wide
Paper Take-up: electrically operated

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Photoelastic Study of Centrifugal Stresses in a Single Wheel and Hub

Object of investigation is to ascertain how accurately the stresses in a single wheel with integral hub are determined by the modified plane-stress theory

by R. Guernsey

ABSTRACT—Results of a photoelastic study of centrifugal stresses in a single wheel with integral hub are given. Stress distributions are determined on the bore and lateral surfaces, and on several radial interior lines. The results are compared with theoretical stresses.

Introduction

Steam-turbine rotors often consist of a number of wheels machined integrally on a common shaft. In the design of such rotors it is necessary to calculate the elastic stress resulting from rotation at operating speed. The rotor geometry creates a three-dimensional state of stress which is impossible to determine by any exact analytical method. Therefore, the stresses are determined approximately by means of generalized plane-stress theory. Under this theory, it is assumed that axial components of stress vanish throughout the volume, and the remaining components of stress do not vary in the axial direction. Changes in the thickness of the wheel are taken into account, a departure from ordinary plane theory.

In applying this theory to a multiwheel rotor, it is assumed that a portion of the shaft on either side of a given wheel acts as reinforcement for that wheel. The resulting wheel and hub combination is then treated as an independent unit for the purpose of the stress calculation. The object of the investigation described in this paper was to determine how accurately the stresses in such a wheel and hub are determined by the modified plane-stress theory. Photoelastic models of a typical wheel and hub were made and centrifugal stresses were frozen into the models. The stresses in the models were then determined and compared with the calculated stresses.

Model Geometry

The geometry of the models was kept as simple as possible in order to minimize difficulties in applying the theory. In actual multiwheel rotors, the wheels are often flared, the shaft may have different diameters on either side of the wheel, and various types of compound fillets may be used at the junction of wheel and shaft. Such geometric features add uncertainties in the calculations. To avoid such uncertainties, the test model was made a simple parallel-sided wheel with a hub of constant diameter. The dimensions are shown in Fig. 1. This design has roughly the proportions of a wheel used in the low-pressure stages of a large steam turbine.

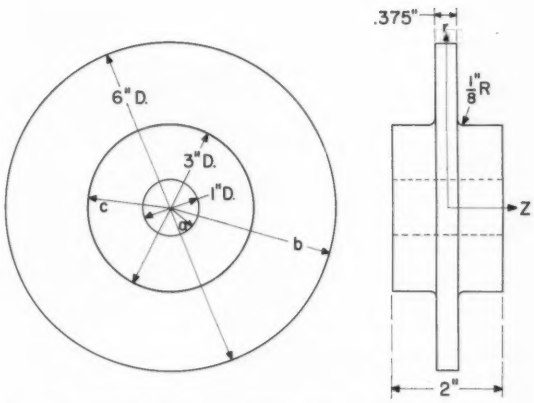

Fig. 1—Geometry and dimensions of models

Theoretical Stress Distribution

Since the design adopted consists essentially of two parallel-sided disks fastened together, the stresses can be determined by application of the generalized plane-stress equations for a rotating disk. The general equations[1] for the wheel are:

$$\sigma_r = K + \frac{D}{r^2} - \frac{3+\nu}{8}\rho\omega^2 r^2 \qquad (1)$$

$$\sigma_\theta = K - \frac{D}{r^2} - \frac{1+3\nu}{8}\rho\omega^2 r^2 \qquad (2)$$

where

σ_r = radial stress component, psi.
σ_θ = tangential stress component, psi.
ν = Poisson's ratio.
ρ = mass density, lb sec^2/in.^{4}
ω = rotational speed, radians/sec.
K, D = constants to be determined.
r = radial polar coordinate, in.

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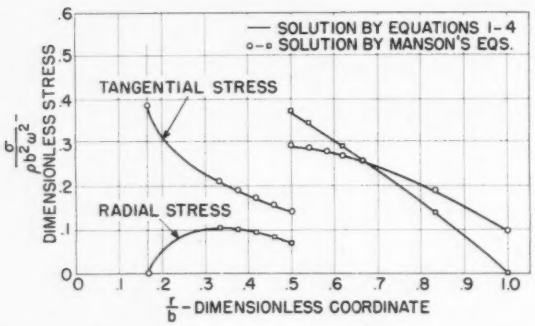

Fig. 2—Comparison of stresses obtained by the two methods of calculation

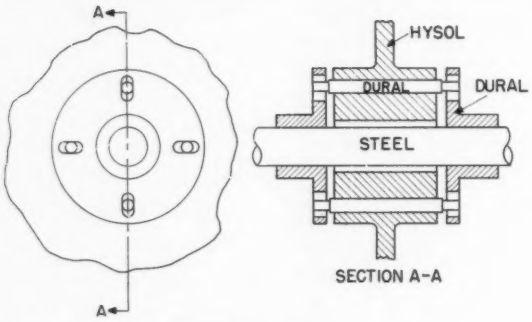

Fig. 3—Method of support for Model 1

The same two equations with different constants apply to the hub.

$$\sigma_r' = k + \frac{d}{r^2} - \frac{3+\nu}{8}\rho\omega^2 r^2 \quad (3)$$

$$\sigma_\theta' = k - \frac{d}{r^2} - \frac{1+3\nu}{8}\rho\omega^2 r^2 \quad (4)$$

σ_r' and σ_θ' are the stress components in the hub. The boundary conditions at the inner and outer diameters are:

$$\sigma_r' = 0 \text{ when } r = a \quad (5)$$

$$\sigma_r = 0 \text{ when } r = b \quad (6)$$

An approximate continuity condition for the radial stresses at $r = c$ is

$$\sigma_r' = \frac{t_{\text{wheel}}}{t_{\text{hub}}}\sigma_r \quad (7)$$

where t is the thickness.

At the junction of wheel and hub, the displacement continuity requirement is:

$$u_{\text{hub}} = u_{\text{wheel}} \quad (8)$$

where u is the radial displacement.

Condition (8) may be rewritten in terms of the stresses since at all points

$$u = \frac{r}{E}(\sigma_\theta - \nu\sigma_r)$$

where E is the modulus of elasticity. Therefore,

$$(\sigma_\theta' - \nu\sigma_r')_{r=c} = (\sigma_\theta - \nu\sigma_r)_{r=c} \quad (9)$$

Boundary conditions (5) and (6), together with continuity conditions (7) and (9), are sufficient for the determination of the four constants, K, D, k and d. The stresses for any value of r can then be determined from eqs (1) through (4).

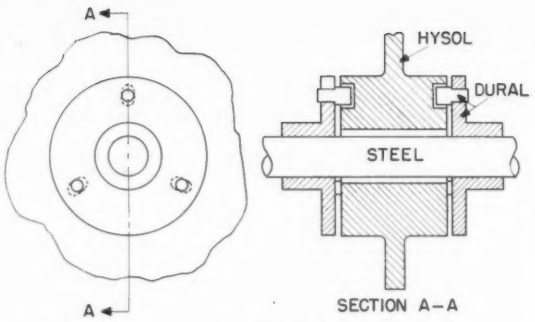

Fig. 4—Method of support for Model 2

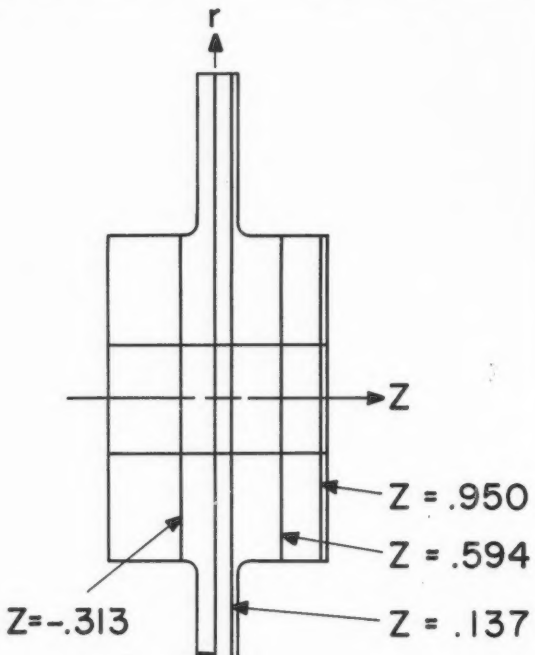

Fig. 5—Planes on which experimental stresses were determined

S. S. Manson has developed a somewhat different method for computing stresses in a rotating disk with variable thickness.[2] With his method, it is possible to determine both centrifugal and thermal stresses in a disk, taking into account changes in thickness, modulus of elasticity and coefficient of expansion. Since the problem under consideration here concerns only centrifugal stresses, it represents a greatly simplified case. Nevertheless, the calculations are most readily performed by an electronic computer. The stress distribution for the test rotor was calculated by the Large Steam Turbine-Gen-

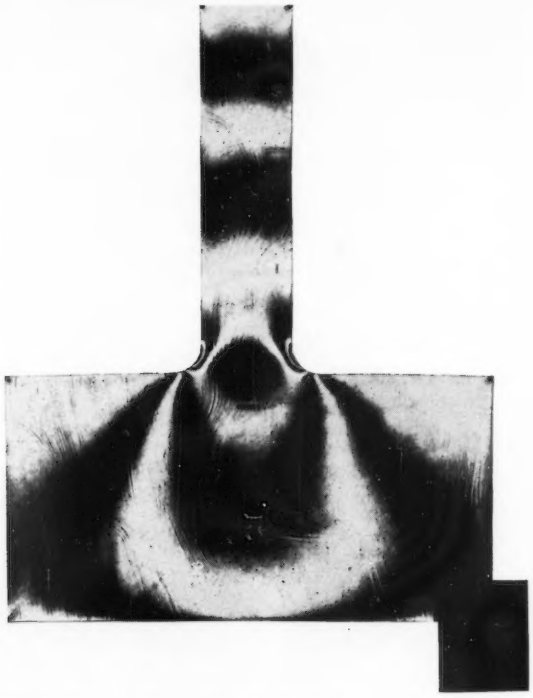

Fig. 6—Stress pattern of longitudinal slice

erator Department of the General Electric Co. at the author's request.

Figure 2 shows the stress distribution in dimensionless form as obtained from both sets of calculations. The solid line represents the solution by the first method; the circles represent the solution by the Manson procedure. It is clear that the two methods yield identical results. However, the first method rapidly becomes cumbersome as the number of thickness changes increases, and the computer solution of Manson's equations is preferable.

The most noteworthy feature of the calculated distribution is the discontinuous change in both components of stress at the junction of wheel and hub. This discontinuity is brought about by the artificial continuity condition on σ_r imposed at that point to account for the sudden change in thickness. It should also be noted that the calculated radial stress exceeds the tangential stress for a short distance just outside the junction.

Test Procedure

Two models were used in carrying out the experimental analysis. They were identical in geometry but differed in the method used to support and to spin them during the stress-freezing cycle. The models were machined from flat sheets of Hysol 6000-OP, an epoxy resin supplied by the Hysol Corporation, Olean, N. Y. Machining to the dimensions of Fig. 1 was easily accomplished on a lathe with standard techniques.

Figure 3 shows the method used to mount Model 1. Four $^1/_4$-in. holes, 90 deg apart, were drilled through the hub. Dural pins passed through these holes and fitted into radially slotted openings in two Dural flanges, one at each end of the rotor. The slotted openings in the flanges permitted the rotor to expand radially as required by thermal expansion and centrifugal stresses. The pins had small shoulders to retain them in position axially. The flanges were mounted on a $^3/_4$-in. horizontal steel shaft which passed through the bore and was supported by ball-bearing pillow blocks mounted in the oven.

After Model 1 had been analyzed, it was felt that the Dural pins passing through the hub might have added somewhat to the loading, and also might have stiffened the hub unnaturally. Therefore, a second model was made and mounted in an entirely different manner as shown in Fig. 4. Three shallow radial slots, 120 deg apart, were machined in each end of the hub. Flat projections fixed to the mounting flanges fitted into these slots and supported the model. Sufficient clearance was allowed in the slots to permit the necessary radial and axial expansions to take place freely. The rest of the setup was the same as for Model 1. With this type of mount, there was no stiffening of the rotor hub.

The steel shaft was rotated by a motor which was connected directly to the shaft through a flexible coupling. The speed of the motor was held constant by an adjustable electronic speed regulator. This is a rectifier unit with tachometer feedback which drives a d-c motor from an a-c source and closely controls the speed at any preset value. The test speed was 3000 rpm for both models.

The thermal program was approximately the same for both models, consisting of a 3-hr rise time to 270° F, an 8-hr soaking period and a 36-hr cooling period. Once the critical temperature was reached, the rotors were spun continuously until the end of the thermal program was reached. Both rotors ran smoothly at all times, and very little runout was observed.

Upon completion of the stress-freezing program, the models were sliced. One longitudinal and four transverse slices were removed from Model 1, while from Model 2 one longitudinal and five transverse slices were cut. The locations of the slices are shown in Fig. 5. The slices were cut from the wheels with a band saw and reduced to the desired thickness by machining with a fly cutter. The thickness of all slices was about 100 mils.

Stress patterns of all slices were photographed for a permanent record. Figure 6 shows the pattern of the longitudinal slice. This pattern gives the difference between the principal stresses lying in the longitudinal plane. Along the bore surface and hub periphery, where $\sigma_r = 0$, it gives σ_z directly. Along the lateral surfaces, where $\sigma_z = 0$, it gives σ_r directly. Figure 7 shows the stress pattern of the

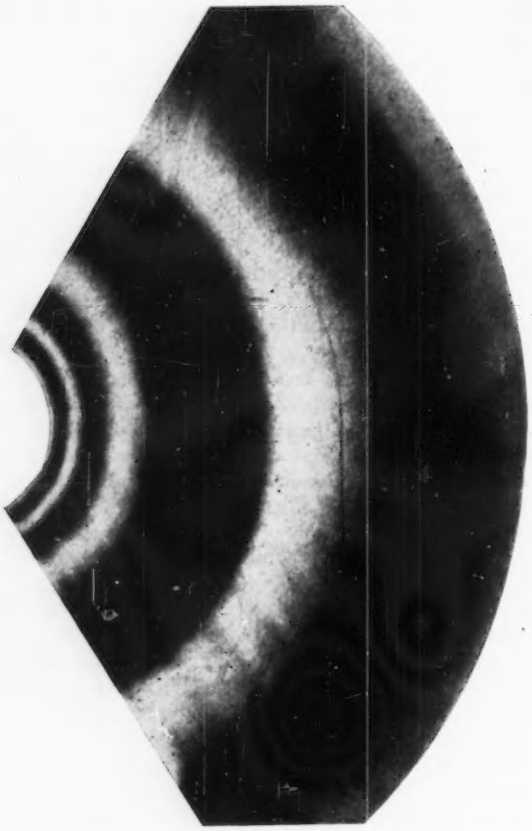

Fig. 7—Stress pattern of transverse slice at midplane of wheel

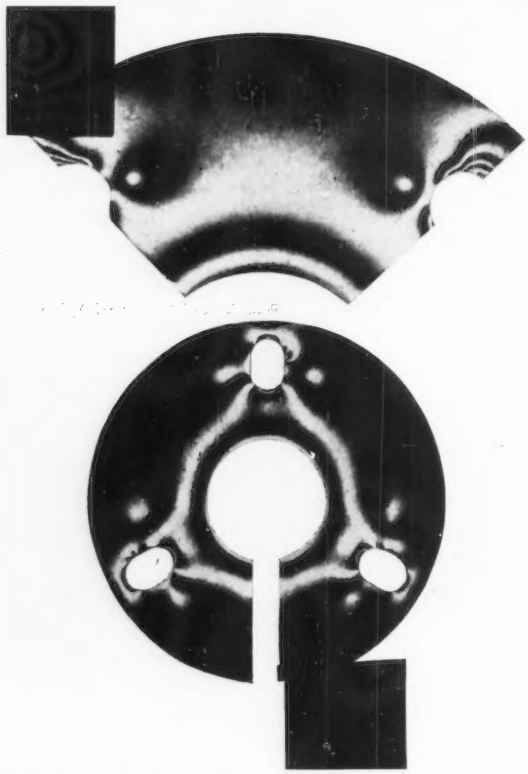

Fig. 8—Stress patterns of slices from end of hub for Models 1 and 2

transverse slice at the midplane of the wheel. Values of $\sigma_\theta - \sigma_r$ can be determined from this slice, and at the free boundaries σ_θ itself. Figure 8 shows patterns of slices taken from the end of the hub in each model. The differing local effects resulting from the two mounting systems are apparent.

Bore Stress Distribution

The first objective was to determine the axial distribution of tangential bore stress for comparison with the calculated value. The bore stresses were determined from each of the transverse slices by measuring the fringe order and multiplying by the known fringe value. Figure 9 shows the distribution for the two models. These results show that the bore stress diminishes toward the ends of the hub as is to be expected. The difference between the two curves is probably a consequence of the difference in the mounting systems.

The maximum dimensionless bore stress was found to be 0.420 in both models. This is 12.5% greater than the calculated value of 0.373. The average bore stresses, 0.370 for Model 1 and 0.356 for Model 2, are close to the calculated value. These results indicate that the generalized plane-stress method of calculation gives a reasonably good estimate of maximum bore stress, although it is slightly nonconservative. It gives a very good estimate of the average bore stress.

Stress Distribution on Radial Lines

The next objective was to determine stress distributions on radial lines and compare with theory. The interior stresses were calculated by numerical integration of the first partial differential equation of equilibrium in cylindrical coordinates for the axi-symmetric case. The details of the method are given in the Appendix. With this method, the stress distribution can be determined on each of the radial lines defined by the intersection of the transverse slices with the longitudinal slice.

Stresses were determined on all possible lines in the two models. It was found that within the $^3/_8$ in. thickness of the wheel, results from the two models were identical. In the hub region there was some difference. Results given here were taken from Model 1 in the wheel and Model 2 in the hub.

Figures 10, 11 and 12 show the experimentally determined tangential, radial and axial stresses, respectively for various values of Z. For purposes of comparison, the calculated distribution arrived at earlier is also shown, as well as the distribution that would exist in the hub if no wheel were attached to it.

There are two static checks that can be made on

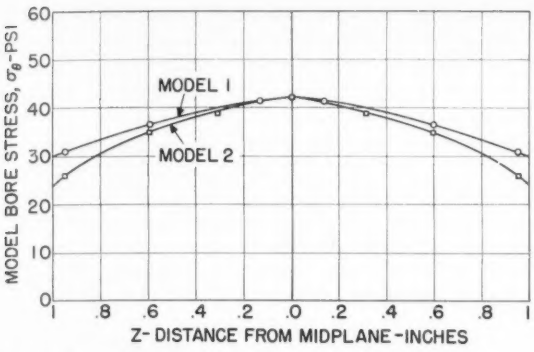

Fig. 9—Axial distribution of tangential bore stresses

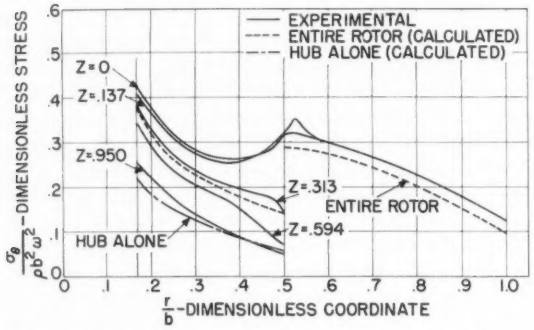

Fig. 10—Radial distribution of dimensionless tangential stresses on several planes

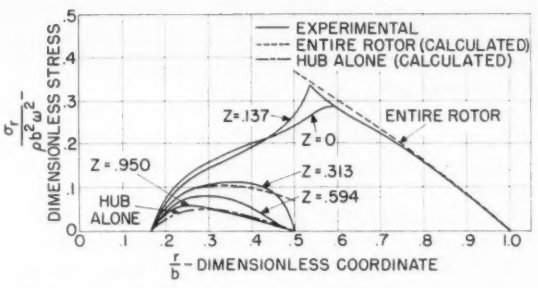

Fig. 11—Radial distribution of dimensionless radial stresses on several planes

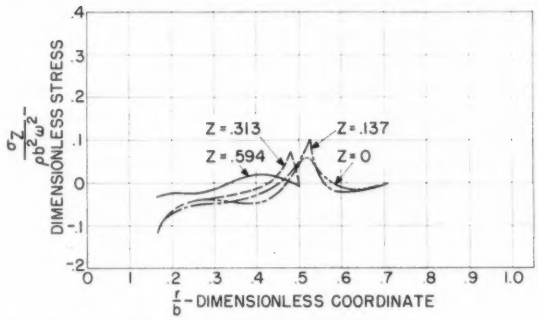

Fig. 12—Radial distribution of dimensionless axial stresses on several planes

these stresses. The total force generated by the tangential stresses acting on the longitudinal cross-sectional area should equal the calculated bursting force, and the net axial force acting on the transverse cross-sectional area should be zero. The calculated bursting force was 117.1 lb. The force generated by the experimental tangential stresses was found to be 117.0 lb—excellent agreement. On most of the sections, the experimental axial stresses were found to yield some net force. However, relatively small changes in the measured stresses would have reduced these forces to zero, as required. Furthermore, the indicated average axial stress was quite small. These static checks were considered satisfactory.

A further check on the accuracy of the boundary stresses is provided by the mechanical strain in the model. The displacements at the inner and outer diameters are easily established by measurement. At the inner and outer diameters, the displacement predicted by the stresses can be determined from the equation

$$u = \frac{r}{E}(\sigma_\theta - \nu\sigma_z)$$

Table 1 shows how the measured and calculated displacements compare.

The agreement is seen to be quite good at all points. In view of the good static and mechanical checks, it seems probable that the experimental stresses are reasonably accurate.

TABLE 1—COMPARISON OF DISPLACEMENTS
$E = 2300$ psi, $\nu = 0.5$

r, in.	z, in.	$\sigma\theta$, psi	γ_z, psi	—DISPLACEMENT— Measured	Calculated
0.5	0	42.5	−11.8	0.0100	0.0105
	1	26.5	0	0.0060	0.0058
3.0	0	12.7	0	0.0160	0.0166
1.5	1	5.3	0	0.0038	0.0035

Inspection of the tangential-stress distribution discloses that the stresses near the wheel midplane are considerably higher than the calculated stresses. It is also clear that the discontinuity in the calculated stresses is replaced by fairly steep gradients near the junction of wheel and hub. Furthermore, contrary to the theory, the tangential stress always remains greater than the radial stress, although they are nearly equal at the junction. The measurements also disclose the presence of a tensile axial stress near the junction, resulting in an approach to a condition of hydrostatic tension at that point. At the bore, the axial stress is compressive, reaching a maximum at the midplane.

Considering the curves in order of increasing values of Z, one can see that the tangential and radial stresses decrease rapidly and approach the values

appropriate to the hub rotating by itself with no wheel attached. If the hub had been slightly longer, it is probable that the stresses would have leveled off at that value.

Figure 13 shows the distribution of boundary stresses along the surface of the rotor. The radial stresses were read directly from the stress pattern of Fig. 6. The tangential stresses were determined by combining data from observations made at normal incidence and at oblique incidence along the boundary.[3] It is seen that the largest tangential and radial stresses occur on the free boundary at the fillet between wheel and hub, as one would expect. The maximum stresses are located near the outer starting point of the fillet. Stresses decrease rapidly at points further around the fillet toward the hub. The tangential stress also decreases rapidly to small values on the hub periphery.

It is worth noting that, in the geometry studied here, the stresses at the fillet are actually greater than the maximum bore stress. In designing steam-turbine rotors it is customary to gradually increase the thickness of the wheel as the junction with the hub or shaft is approached. This has the effect of reducing the stress peaks which otherwise would occur. In such rotors, the maximum stress is generally found at the bore.

It has been demonstrated that the calculated stresses do not yield a very true picture of the stress distribution on individual interior lines. However, it was hardly expected that they would do more than indicate the average stress over the thickness of the rotor. Figure 14 indicates how the calculated stresses compare with the axial average of the measured stresses. The solid line represents the calculated stresses. The circled points show the axial average of the experimental tangential and radial stress at several stations. It is seen that, within the hub radius, the calculated stresses agree remarkably well with the measured average stresses. Outside the junction the agreement is not quite so good, as the calculations underestimate the true average tangential stress.

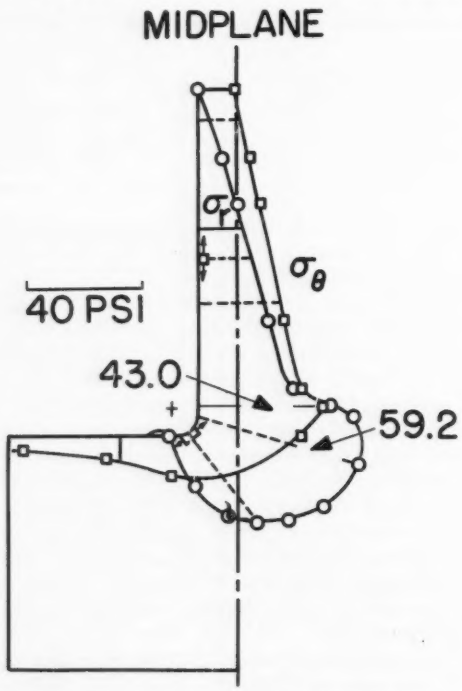

Fig. 13—Distribution of stresses on surface of wheel

Conclusion

It has been shown that the photoelastic method of stress freezing can be readily applied to the study of three-dimensional rotors. Interior stresses can be determined reliably by the numerical-integration procedure outlined.

Methods of calculation based on the generalized plane-stress equations fail to give a true picture of the actual stress distribution on individual radial lines. The discrepancy is particularly large near the junction of wheel and hub. However, stresses calculated by these methods do represent fairly well the average stress across the wheel thickness, particularly in the region lying within the hub radius. At the bore surface, the calculated stress may underestimate the true maximum stress by 10 to 15%.

The methods of calculation used here assume that there are no axial normal stresses. The results show that axial stresses do exist in a rotor of the proportions tested. They are not large enough to be important from the standpoint of strength. However, at the bore the axial stress might contribute substantially to the displacement. This could be significant if a shrink fit were to be used.

In the test rotor the absolute maximum stress was found in the fillet at the junction of wheel and hub. This could also be true in rotors of different proportions. It is therefore good practice to flare the wheel to greater thickness near the junction.

APPENDIX

Procedure for Determining Interior Stresses

The first differential equation of equilibrium in cylindrical coordinates for the axisymmetric case is

$$\frac{\partial \sigma_r}{\partial r} + \frac{\partial \tau_{rz}}{\partial z} + \frac{\sigma_r - \sigma_\theta}{r} + \rho\omega^2 r = 0 \qquad \text{(A1)}$$

where

σ_r, σ_θ = normal stress components.
τ_{rz} = shearing stress component.
r = radial polar coordinate.
z = axial coordinate.
ρ = mass density.
ω = rotational speed.

Integrating formally with respect to r between limits r_0 and r_1 we obtain

$$\sigma_{r_1} = \sigma_{r_0} - \int_{r_0}^{r_1} \frac{\partial \tau_{rz}}{\partial z}\, dr - \int_{r_0}^{r_1} \frac{\sigma_r - \sigma_\theta}{r}\, dr - \frac{1}{2}\rho\omega^2(r_1^2 - r_0^2) \qquad \text{(A2)}$$

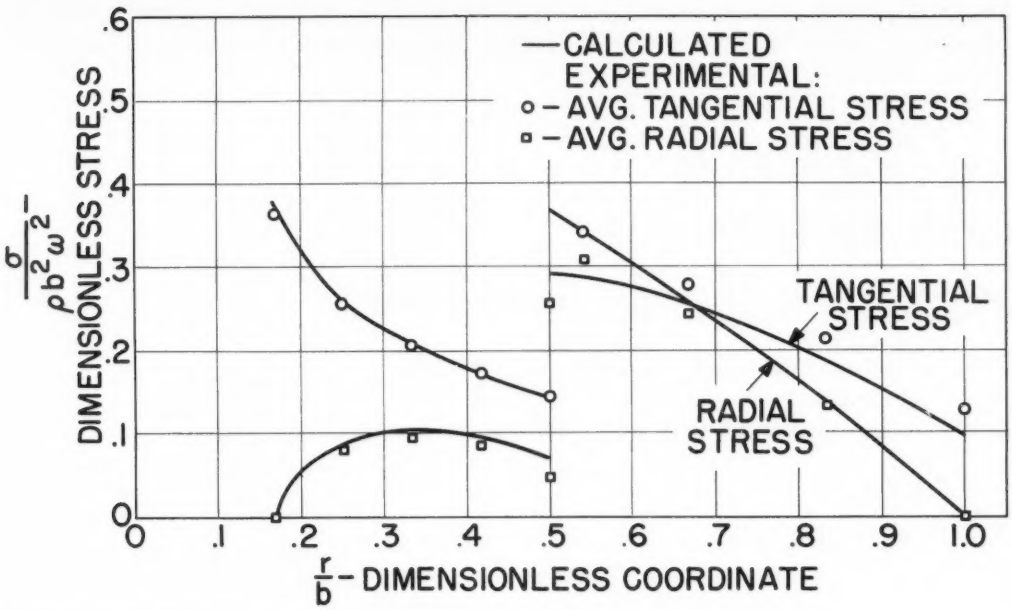

Fig. 14—Comparison of average experimental stresses with calculated stresses

The body force contribution in the last term can be calculated exactly with no difficulty. The integral terms must be calculated approximately by finite difference procedures. In finite difference form eq (A2) becomes

$$\sigma_r = \sigma_{r_0} - \sum_{r_0}^{r_1} \frac{\Delta\tau_{rz}}{\Delta z}\,\Delta r - \sum_{r_0}^{r_1} \frac{\sigma_r - \sigma_\theta}{r}\,\Delta r - \frac{1}{2}\,\rho\omega^2(r_1^2 - r_0^2) \quad \text{(A3)}$$

To establish the first summation, the term $\Delta\tau_{rz}/\Delta z$ must be plotted as a function of r. This quotient is established by determining τ_{rz} along two auxiliary lines in the rz-plane. The auxiliary lines lie on either side of the line of integration and as close to it as possible. Measurements of fringe order n and isoclinic parameter ϕ along these lines leads to determination of the shear stress τ_{rz} through the equation

$$\tau_{rz} = F\,\frac{n}{2}\sin 2\phi \quad \text{(A4)}$$

where F is the model fringe value.

At the same time, measurement of fringe orders and isoclinic parameters along the line of integration itself yields the stress difference $\sigma_r - \sigma_z$ through the equation

$$\sigma_r - \sigma_z = Fn\cos 2\phi \quad \text{(A5)}$$

As in the shear-difference method,[4] the quantity $\Delta\tau_{rz}/\Delta z$ is established by taking the difference between the shearing stresses on the auxiliary lines and dividing by the line spacing Δz. This quantity is plotted as a function of r. The partial area under the curve for any interval Δr gives the value of $\Delta\tau_{rz}/\Delta z\,\Delta r$ for use in the summation.

The second summation requires knowledge of $(\sigma_r - \sigma_\theta)/r$ as a function of r. This is established by measuring the radial distribution of fringe orders on the appropriate transverse slice; calculating $\sigma_r - \sigma_\theta$; forming the quotient $(\sigma_r - \sigma_\theta)/r$ and plotting as a function of r. The partial area under this curve for any interval Δr gives the value of $[(\sigma_r - \sigma_\theta)/r]\,\Delta r$ for use in the summation process.

Summation can begin at the bore where $\sigma_r = 0$ and proceed step by step to the outer periphery. Here again $\sigma_r = 0$ and this serves as a check on the accuracy. Before proceeding any further, this condition must be satisfied. With the value of σ_r established at all points on the line, it is a simple matter to compute σ_θ and σ_z from the known values of $\sigma_r - \sigma_\theta$ and $\sigma_r - \sigma_z$.

It should be noted that, for best results, fringe orders and isoclinic parameters must be measured with high accuracy. This is best accomplished by the use of photometric methods.[5] Uniformly excellent results have been achieved in a large number of cases when such methods were used.

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Testing Techniques for Full-scale Missile Structures Under Simulated Re-entry Environment

Adequacy of missile structures for re-entry flight can now be evaluated by means of unique laboratory programs which approach the comprehensiveness of full-scale flight test programs

by R. T. Nichols

ABSTRACT—The intricate pattern of stresses and strains induced in missile structures by the combined environments encountered during re-entry of the earth's atmosphere has necessitated the establishment of unique testing techniques and facilities for evaluating missile performance during this severe phase of flight.

Introduction

The launching of the Pioneer IV into orbit around the sun was an important fulfillment in the quest for interplanetary travel by manned space vehicles. Before attempting flights of this nature, man must first solve the problem of returning safely to his own domain. The successful re-entry by United States ballistic missiles during the past two years is indicative of substantial progress in this pursuit. These achievements have most assuredly been assisted by laboratory test programs performed on missile structures to evaluate their adequacy for re-entry flight.

Because the methods used for testing early missile designs did not adequately simulate re-entry environment, it became mandatory that new techniques be developed for simulating these conditions in the laboratory. Recognizing the importance that laboratory testing must play in the solution of the re-entry problem, Chrysler Missile Division in 1956 established the simulated atmospheric re-entry testing facility. This facility has enabled Chrysler Missile Division to adopt the more advanced environmental simulation techniques, so essential to the accurate re-entry testing of space vehicles.

Evolvement of the Laboratory-test Philosophy

One of the first questions invariably raised when discussing missile performance is: "What is the necessity of performing laboratory tests when, in the final analysis, flight-test performance is of prime importance?" A review of early missile development clearly gives the answer by showing the results of inadequate laboratory testing before missile flights are made. World War II rockets had a notorious record of failures in their early firings. A large number of the malfunctions can be attributed directly to extremely limited development time and, consequently, inadequate preflight test programs. This past history was a significant factor in the evolvement of the laboratory-test philosophy practiced in development of United States tactical missiles.

Discussion of Laboratory Simulation Techniques

Although much has been done analytically to predict the behavior of missile structures, the confidence that can be placed in a theoretical analysis of the stresses and strains encountered during re-entry flight is limited. The assortment of analytical quantities to be evaluated, such as elastic variations, transient thermal and mechanical strains, variable heat transfer, specific heat and thermal-conductivity factors, defies the most advanced methods of analytical solution. Since it is economical from both time and money aspects to evaluate as many systems as possible prior to flight testing, the establishment of testing techniques and facilities capable of testing missile structures under the combined environment encountered during re-entry flight became of prime importance.

Before detailing the advanced techniques used in re-entry testing, it is desirable to define the principal environmental parameters being duplicated. The principal parameters are: temperature, load, and pressure, of transient nature as depicted in the typical flight curves, Fig. 1. As mentioned in the introduc-

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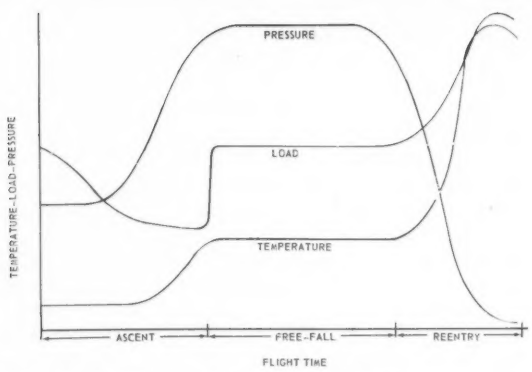


Fig. 1—Typical flight-environment parameters

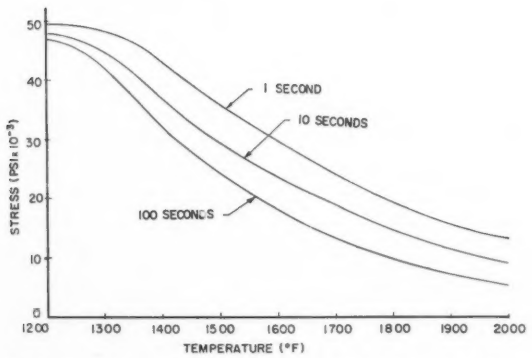


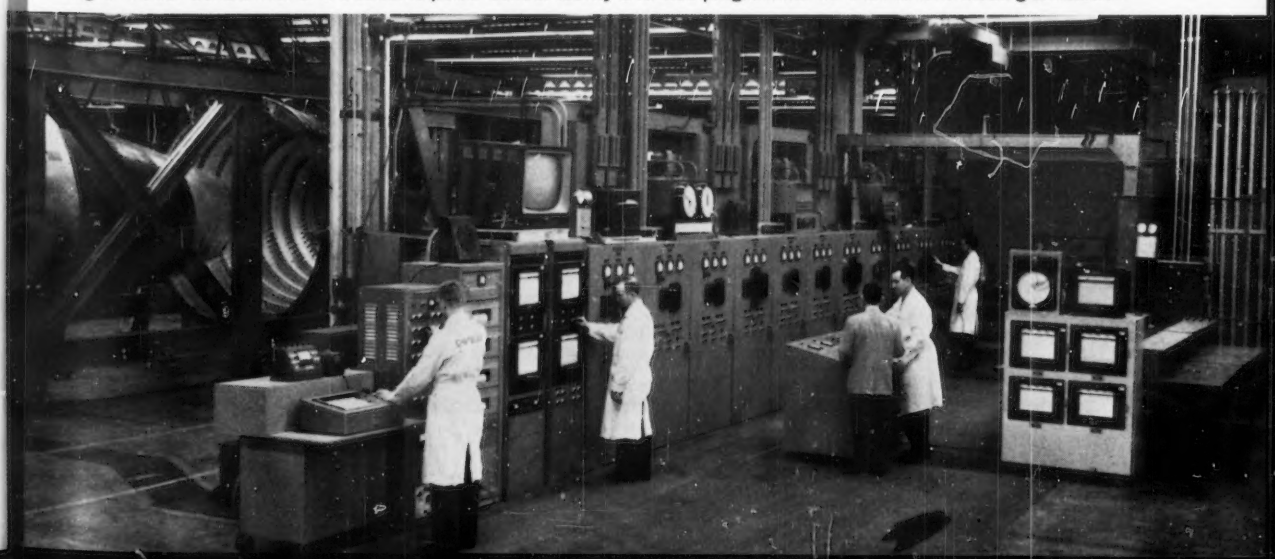
Fig. 2—Stress-rupture curves for Type 321 stainless steel

tion, the missile experiences the most severe environmental conditions during the re-entry phase of flight. Since all parameters are time dependent, it is essential that the testing method closely duplicate the flight temperature–load–pressure–time history. The reason for this requirement is that the strength of the structure, which is related most closely to the stress-rupture and strain-rate properties of the material, is time dependent at the temperatures encountered during flight. As an example, by referring to Fig. 2, it is apparent that Type 321 stainless steel will not fail in flight if a stress level of 35,000 psi is applied and relieved in one second at a temperature of 1500° F. If, during test, however, the structure is heated at a slower rate than occurs during flight, or the loading which induces the 35,000 psi mechanical stress is maintained for an excessive time period, a rupture would develop which would not be indicative of a design deficiency. It is, therefore, of utmost importance that heating and loading control be sufficiently sophisticated to permit accurate duplication of the flight temperature–load–pressure–time relationships. The technique used for simulating these environmental parameters and the test equipment necessary for performing these tests are described in detail in the following section.

Simulating the Thermal Environment

The determination of the flight temperature–time curve which simulates the re-entry heating (Fig. 1) is derived from an analytical solution of the heat-flow equations in which the net heat in the specimen is the difference between the heat transferred to the skin from the boundary layer and the heat lost by the specimen through radiation. The high rates of energy input to the specimen, required to simulate the predicted re-entry heating curve, demanded consideration of heating apparatus with high-output heat-flux densities. Preliminary studies indicated that the heating source must have a heat-flux density of 50–100 Btu/fps for testing the re-entry sections of the present generation of medium-range missiles. (This heating flux is also sufficient to evaluate the ascending phase of flight for almost any ballistic missile.) Several techniques for meeting these requirements were investigated, with the

Fig. 3—Power transformer and electronic power-control facility and load programmer for thermal and loading simulation



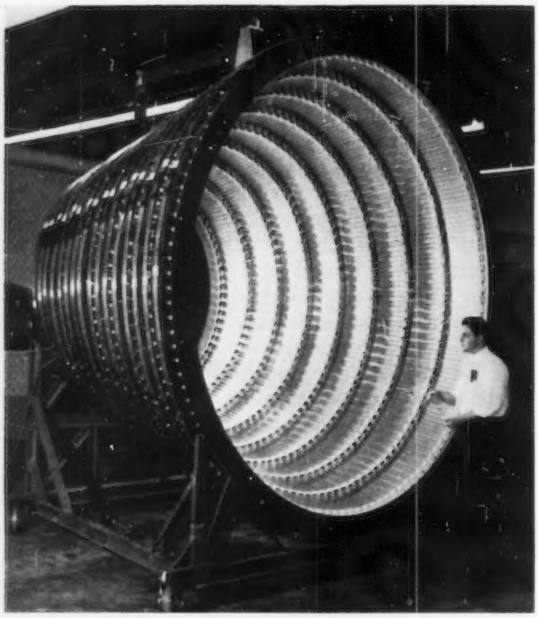


Fig. 4—"Jupiter" missile section environmental heating furnace

tungsten-filament, quartz-enveloped lamps ultimately selected as the most practical and accurate heat source. The heat lamps were chosen, primarily, because of two important features:

1. Low thermal inertia in heating and cooling, which made them highly adaptable to programming.
2. Uniformity of specimen surface temperature made possible by the uniformity of lamp output.

Performance tests of the infrared lamps indicated that heat-flux densities in the neighborhood of 100 Btu/fps are attainable when operated at double the rated voltage. These tests also disclosed an overall efficiency of approximately 70% in terms of the ratio of heat-flux density to input power. On this basis, it was determined that a five million-watt, 3-phase, a-c transformer (Fig. 3) with 400% overload capacity for short periods of time was necessary for a power source to heat large missile sections.

The development of a furnace utilizing these lamps and capable of meeting the desired heating flux, required the inauguration of a test program to determine the effects and interactions of the following design variables:

1. Available power.
2. Lamp density.
3. Lamp spacing.
4. Lamp radiation decay.
5. Furnace reflector characteristics.
6. Dimensional limitations.
7. Cost.

The engineering data obtained from these tests were used in designing radiant-heat furnaces typical of that shown in Fig. 4, which was constructed for an environmental test of a "Jupiter" missile section. This furnace required 1554 quartz infrared lamps mounted in rows parallel with the conical surface of the furnace shell. To improve the heating uniformity of the furnace, the inner surface of the furnace shell was painted with a silicone-based aluminum paint, which provided a specular type of reflector for better diffusion of the radiant energy. Specially designed lamp support clips, partially encased by ceramic insulators, prevented arcing between the terminals distributing the power phases and excessive heating of the sealed lamp ends. The power input to the furnace was distributed to the lamps by heavy copper bus bars. The bus bars were mounted over the exterior of the furnace shell and supported by high-voltage electrical insulators. The power required to operate this furnace at peak output is approximately $3^1/_2$ million watts. It is capable of heating a 200-sq ft aluminum missile skin, 0.050 in. thick to 1000° F in approximately 30 sec.

Temperature-programming Technique and Equipment

The temperature–time history curve or curves selected for the test may include testing of one or more areas of the missile skin and may require full temperature programming from the moment of launching to late in the re-entry phase as depicted in Fig. 1. Initial heating develops during the ascending phase, reaches a peak, then plateaus as the missile free-falls through space. A rapid increase in heating then occurs during the re-entry phase, with a slight temperature decay just before impact. To duplicate this transient heating and cooling, an electronic programmer and power-control system is utilized to program the voltage from the main power transformer to the infrared lamps (Fig. 3). A signal proportional to the desired temperature–time history is programmed into a summing junction which electrically compares this signal to the feedback signal from a thermocouple mounted on the missile skin. These control thermocouples are located at a point sufficiently removed from any rib or stiffener to eliminate their heat-sink effects.

The power-control and regulator system selected for use consists of two inverse-parallel-connected, thyratron-controlled ignitron units. In operation, the error signal from the temperature–time programmer just described energizes the thyratron which, in turn, excites the ignitron and permits power to flow from the power transformer to the radiant furnace. When the specimen is cooler than desired, the programmer signals for an increase in power to the infrared lamps and for a reduction in power when the specimen is hotter than desired. The response of the electronic system required to maintain the desired temperature is sufficiently fast to assure a

smooth and accurate temperature control within ½% of the full temperature range. The 12 channels of the power-control system shown in the photograph, Fig. 3, can deliver 4.5 million watts continuously for 5 min or up to 17 million watts for 3 sec. The advantage of having 12 channels of control is that it permits considerable flexibility in heating missile sections by making differential heating possible over the various missile surfaces. In general, aerodynamic heating causes substantial heat gradients to exist between the forward and aft portions of a missile, which can be accurately duplicated by the 12 independent heating zones.

Simulating the Loading Environment

Of equal importance to simulating the thermal environment is the accurate duplication of the loading environment during the re-entry tests. As discussed previously, it is necessary that test loads be applied in the proper manner and only for the same duration of time as that experienced during flight.

When mechanical forces, simulating aerodynamic loads, are applied to the test specimen, it is essential that the stress distribution induced be as close as possible to stress patterns encountered during flight.

Reasonably accurate stress distributions can be obtained if flight bending-moment loads, shear loads, axial loads and differential-pressure loads are closely duplicated during the test.

The technique used for loading a typical full-scale prototype section is illustrated in Fig. 5. Hydraulic cylinders mounted at the locations shown applied the required loads encountered by the nose cone during re-entry. The re-entry loads and the method of application for this particular test are:

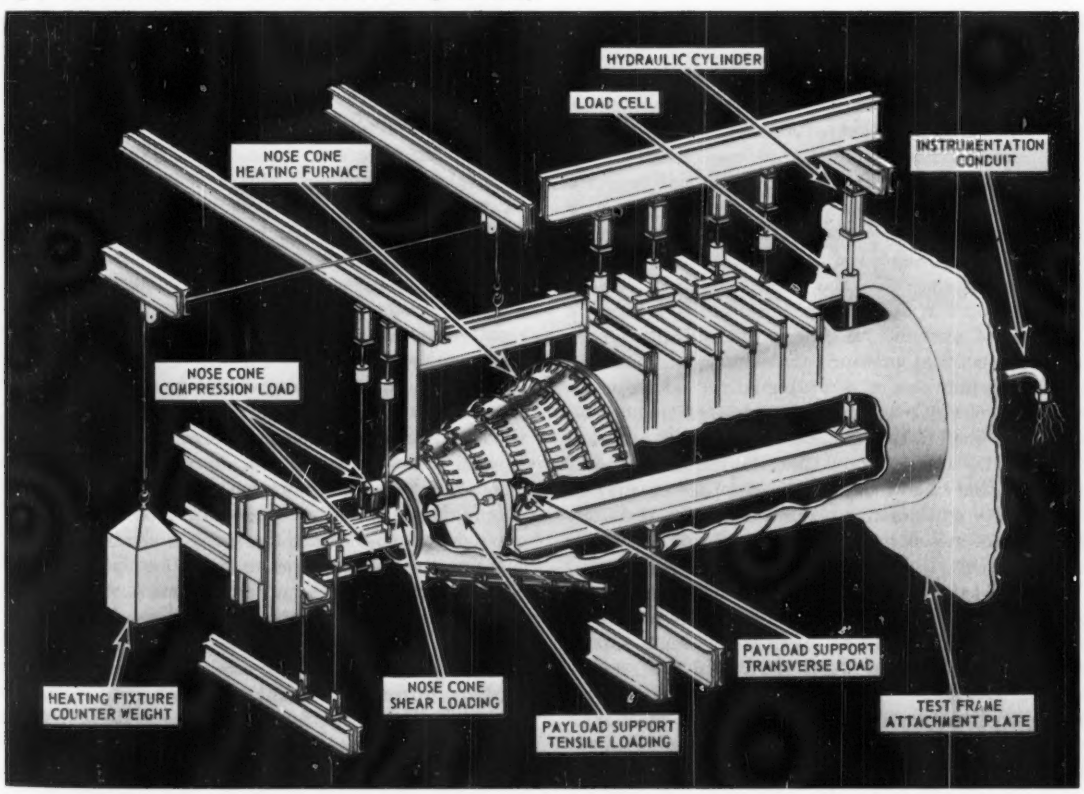
1. Forward inertia load of the payload reacted by the payload support cone; the load was applied through the payload attachment fitting on the payload support cone.

2. Lateral inertia load of the payload reacted by the payload support; in this particular test it was necessary to apply the load through a pivoted beam because of the obstructions presented by the structure configuration and the radiant furnace.

3. Axial compression load on the nose cone caused by drag forces on the missile skin; the load was applied through the stiffened forward-ring frame to distribute uniformly the load around the circumference of the structure.

4. The bending moment and shear loads caused by the angle of attack during re-entry; these loads were simulated by applying shear loads at the for-

Fig. 5—Illustration of nose cone simulated re-entry test setup



ward-ring frame and strap loads at the various sub-structural ring-frame location, aft of the furnace.

Loading-control Technique and Equipment

When closely controlled loads became a necessity for the simulated atmospheric re-entry testing facility in 1956, no known commercial load-control system capable of meeting the testing requirements was available. As a result, an electronically controlled hydraulic servo-valve system was developed at Chrysler Corp. Missile Division. The resulting electrohydraulic load programmer is shown at the left center of the testing facility in Fig. 3. The system is capable of controlling 10 independent loads within accuracy of 2% and will respond to a full-range change of load within $^1/_2$ sec.

The system operates on a typical servomechanism principle. A manual control or programmer generates a signal from a curve drawn with conductive ink on standard graph paper which represents the desired load–time history. This signal is compared electrically with a signal generated by a load cell connected in series with a hydraulic cylinder. Any difference between the signals produces an error signal which is used to control an electrohydraulic servo valve. This valve regulates the hydraulic pressure in the cylinder to correct the error.

The response of this system is extremely fast, permitting rapid recovery from errors and an accurate maintenance of loads in the event of yielding or deflection of any structure.

Many missile shells maintain sea-level pressure within the shell throughout the flight to assure proper operation of guidance and control equipment. Since the structure must withstand, in addition to the thermal and aerodynamic-loading environment, the stresses resulting from the differential pressure between the interior of the shell and transient ambient pressure, it was necessary to develop control equipment capable of reproducing the transient differential pressures. The pressure-control system used is similar in operation to the electro-hydraulic load-control system. In the pressure-control system, an electrical pressure transducer supplies the signal for operation of a double-barrel electropneumatic servo valve which pressurizes or evacuates the missile shell until the desired differential pressure is obtained. In the event that the required rate of pressurization or evacuation exceeds the capacity of the supply equipment, accumulators or vacuum chambers of sufficient volume are utilized.

When pressurization of a test structure is required, a potential safety hazard exists because of the large volumes of air normally involved. To assure a minimal hazard condition during the test, safety precautions are taken. The volume of the section under a test is reduced as much as possible by the insertion of noninflammable foam-glass blocks or specially constructed steel-tank sections. Safety-relief valves are mounted to the specimen to prevent overpressurization. Steel nets or screens are placed adjacent to the test frame to reduce any personnel hazard from metal fragmentation in event of an explosion. In addition, all test personnel is stationed at a safe distance and is required to wear safety goggles, helmets and ear protectors.

Techniques for Evaluating the Effects of Re-entry Environment

Thus far the discussion has been limited to methods of simulating the re-entry environment. Nearly as important are the techniques and apparatus used for determining the results of a test. To be of more value than a go-no-go type of test, quantitative evaluation of the specimen performance is essential. To evaluate a test specimen it is not uncommon to measure continuously over 200 channels of information during re-entry test. The basic structural parameters measured as a result of the applied loads, pressure and heat are strain, pressure, deflection and temperature. The measurement of strain under transient heating is generally recognized as the most difficult to obtain. Considerable strides have been made in strain-gage technology during the past decade; however, satisfactory high-temperature gages for use under high transient heating are not currently available. Although techniques used for other measurements have been more successful, considerable investigation and tests were required to qualify them for use during re-entry tests. The techniques employed to resolve these various measurement problems are presented in detail in the following section.

Strain Measurement

The selection of a strain gage or gages for a particular strain measurement is contingent on the environment to which it will be subjected. Foil or Bakelite gages of the temperature-compensating type have been found to perform satisfactorily at temperatures up to 475° F. Although these strain gages are constructed to compensate for thermal expansion of the material to which they are bonded, complete compensation for all thermal effects is impossible; for example, changes in gage-bonding characteristics or the electrical-resistance changes of the gage element at elevated temperatures may result in indicated strains which do not actually exist. To eliminate these nonexistent strains, an evaluation of each type of strain gage must be made. The evaluation is performed by using a strain-gage tensile specimen in conjunction with an optical strain gage, which measures correct strain. A temperature program is applied to the specimen and an optical strain measurement is taken at various intervals. A continuous plot of the strain-gage output is recorded. After performing a number of tests at various stress levels, an average correction curve of strain versus temperature is determined. The values obtained from the strain-correction curve are

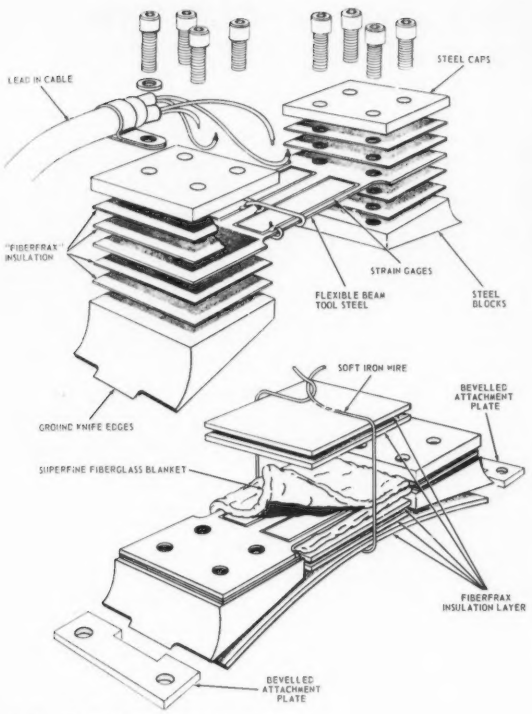


Fig. 6—Off-surface strain transducer

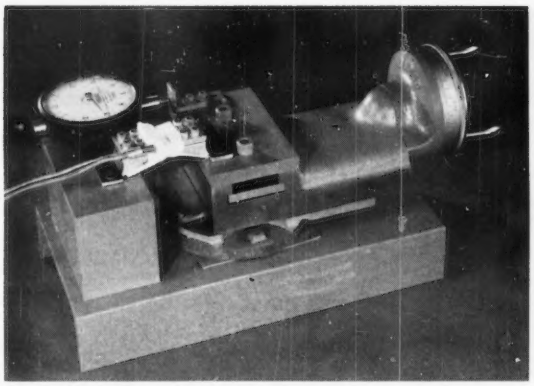


Fig. 7—Strain-transducer calibrator

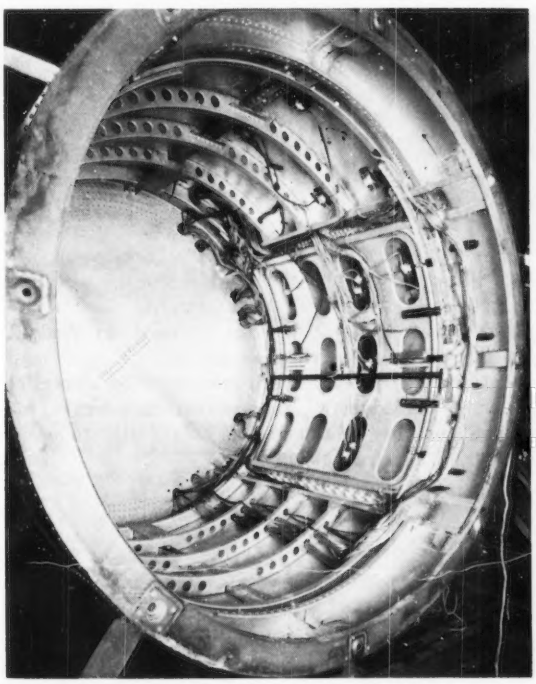


Fig. 8—Off-surface strain transducers mounted in a "Redstone" missile section

then used to obtain the actual nominal strain during the test.

Since transient strains have to be measured at the temperatures above 1000° F normally encountered on the missile skin during re-entry, other methods of strain measurement became necessary. Chrysler Missile Division, therefore, developed an off-surface strain transducer capable of measuring strains over a 3-in. gage length at temperatures up to 1600° F with an accuracy of ±5%. An exploded view of the transducer is shown in Fig. 6.

In operation, four resistance strain gages are bonded to a $^3/_8$-in. wide by 0.032-in. thick strip of high-strength steel and wired in a four-arm bridge to increase the sensitivity and compensate for temperature effects. The gages respond to bending of the steel strip, caused by extension or compression of the knife-edge bases to which it is attached. To permit measurement of tensile strains, the transducer must be compressed initially before inserting between two beveled gage plates (Fig. 6) which are firmly secured to the specimens by screws. The steel strip of the transducer is insulated from the end clips to minimize conduction heating through the base. Heat conduction is further minimized by the small contact area of the knife edges and the relatively large mass of the bases. The strain gages and steel strip of the transducer are shielded from excessive radiant heating by an insulation blanket. Repeated tests have indicated that these insulating methods are effective in preventing the temperature of the steel strip or strain gages from exceeding 300° F with a specimen temperature in excess of 1600° F. The period of heating during these investigations was considerably longer than required during full-scale tests. The operating temperature of the gages, however, was within the compensation range of the four-arm bridge and, therefore, no errors were induced.

The strain transducer is calibrated for strain-gage output vs. specimen strain in a laboratory precision fixture (Fig. 7) by measuring the relative displacement between the knife edges as compared to the electrical output of the four-arm bridge. Since the effects of the high transient temperatures on the linearity of the transducer strain output is neg-

ligible, calibration at room temperature remains valid.

Figure 8 shows a typical mounting and wiring arrangement of several transducers on a section of the "Redstone" missile.

In addition to the strains produced by aerodynamic loading on the missile skin, thermal strains are induced by thermal expansion of the material. Standard coefficient-of-expansion values for a given material, however, are invalid for use in accurately determining the thermal strains, because of the nonlinear variation of the thermal coefficient of expansion with temperature. For this reason, it is necessary that the coefficient-of-expansion values for the test material be determined for the test operating range. These values are obtained by performing elevated-temperature tests in which the re-entry test-temperature history is duplicated on 6-x 6-in. steel pates of the same material as used in the test specimen. The test setup is shown in Fig. 9.

Load and Pressure Measurement

Accurate measurement of the loads applied by the hydraulic cylinders is accomplished with strain-gage-type load cells (Fig. 5) connected in series with the cylinder. This particular type of load cell is commonly used for load measurements where fast response to any change of load with high accuracies is desirable. Aluminum-foil shields are placed over those load cells exposed to radiant heating to maintain their accuracy.

Internal air pressures are measured by electrical pressure transducers at locations sufficiently removed from any conductive or radiant heat to avoid this possible source of error.

Deflection Measurement

The measurement of deflections occurring in a missile structure during a test is of considerable importance. The deflection measurements obtained are frequently utilized to establish the sequence or progression of failure during a test. The payload support cone of the "Redstone" missile shown on the left in Fig. 10 is an example of a failure in which deflection was used as a means of establishing the time of failure initiation. The deflection measurement in this instance was obtained from the relative displacement of the payload support hub located at the center of the payload cone and the cone attachment ring located at its base. Analysis of deflection results permitted accurate determination of the time of nose-cone failure. (The cone on the right in Fig. 10 depicts the results of a subsequent evaluation test performed on a redesigned support cone.) Deflection measurements are normally obtained during the test by extensometers constructed of spring-loaded telescopic tubing mounted between the points of interest. A rectilinear potentiometer attached to the tubing measures the relative motion between the tubes when deflection occurs. Extensometers of this type give good sensitivity and measurement accuracy (within $\pm 5\%$). Those potentiometers exposed to radiant heating are wrapped with an insulation material to avoid temperature-induced errors.

Temperature Measurement

Because of the transient nature of high-temperature testing, a temperature transducer must not only possess high accuracy but must also exhibit

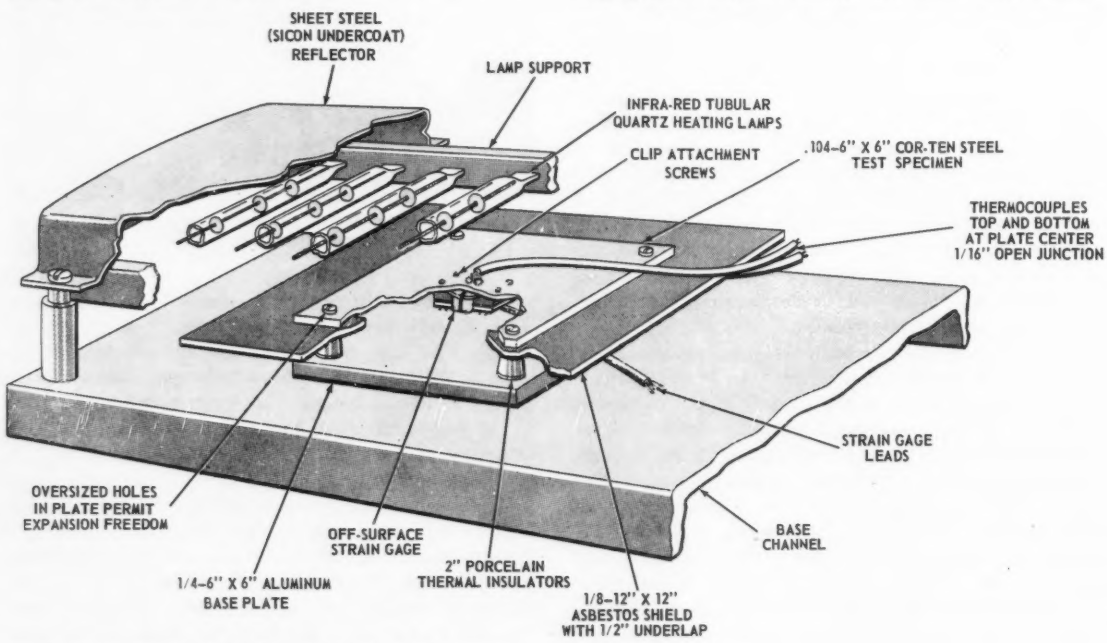


Fig. 9—Thermal coefficient of expansion-test setup

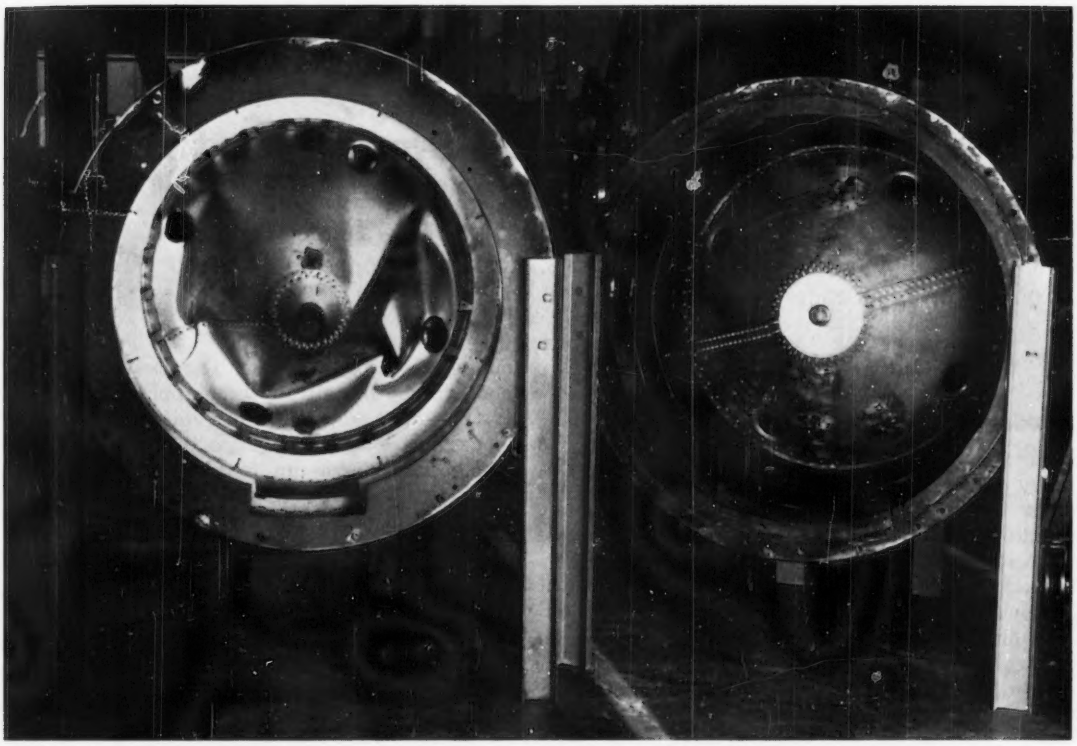


Fig. 10—Simulated re-entry test results on a "Redstone" prototype and revised-design payload support cone

fast response to temperature change. Thermocouples were determined by test to be the most practical transducer because of their ease of application and excellent performance in meeting these requirements. The conventional twisted hot-junction thermocouple, however, resulted in considerable temperature-measurement errors when exposed to infrared radiation. The more recently developed "open-junction" probe, in which the lead wires are welded to the specimen surface in close proximity to each other, assures accurate temperature measurement. Chromel-alumel thermocouple wire was chosen over other types because of excellent repeatability, linearity and sensitivity in the required temperature range.

Recording of Measurements

During the testing of a major missile section, the measurements of interest such as strain, temperature, deflections and loads are recorded continuously on strip charts and standard oscillographic equipment. On major test programs, most of the measurements are usually recorded continuously, then reduced by electronic data readers and computers for later analysis.

In addition to the recording equipment, motion-picture cameras are mounted at various positions outside and inside of the test specimen to allow visual recording of the test for additional verification or detection of test-specimen behavior. Closed-circuit television is used to aid monitoring of the test activity in the interior of the missile structure.

Summary

The magnitude of stresses and strains induced in missile structures by the combined environments encountered during re-entry of the earth's atmosphere has necessitated the establishment of unique testing techniques and facilities for evaluating missile performance. The development of controlled heating, loading and pressurizing systems capable of closely simulating the re-entry environments and the advancements of structural strain- and temperature-measuring techniques have permitted laboratory evaluation of full-scale missile sections under re-entry conditions. As a result of these advancements in engineering technology, the structures produced for today's missiles can be evaluated for service by laboratory programs which approach the comprehensiveness of full-scale flight test programs.

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On Saint Venant's Principle Under Dynamic Conditions

Paper presents results from preliminary experiments which were undertaken to determine whether, under dynamic conditions, there exists a principle similar to the one which exists under static conditions.

by P. D. Flynn and M. M. Frocht

Introduction

Saint Venant's principle is fundamental in the theory of elasticity, and it will be assumed that the reader is familiar with this principle under static conditions. Consider, for example, two struts supported on the ends and carrying equal forces of different distributions on the opposite ends. Experiments[1] show that even in the extreme case when one strut is subjected to a uniform traction having a resultant R and the other strut is subjected to a concentrated axial load equal to R, the states of stress become essentially the same in both struts at a distance from the concentrated load equal to approximately $1.25d$, where d is the width of the bar. Under static conditions, equivalent force systems produce different stresses only in the immediate vicinity of the loads.

The purpose of this paper is to present results from preliminary experiments which were undertaken to determine whether a similar principle exists under dynamic conditions, i.e., when struts are subjected to the impact of a moving hammer. It should be noted that, under static conditions, stresses are compared for equal resultant loads, whereas under impact conditions, the significant factor seems to be the velocity of the hammer. The comparison is made, therefore, not for equal loads but for equal velocities of impact.

The experimental results on the existence of a Saint Venant's principle under dynamic conditions are based on a comparison of photoelastic stress patterns obtained by means of streak photography. As explained in a previous paper,[2] the method of streak photography enables one to obtain continuous records of the changes in birefringence along arbitrary lines in plane-stress systems. The interpretation of the stress patterns so obtained is relatively simple, and there is no difficulty in determining the fringe orders. The method of streak photography has already been applied to the study of stress-wave propagation in a uniform bar subjected to uniform longitudinal impact[3] and to the determination of maximum tensile stresses in simply supported beams under central transverse impact.[4]

In this paper, streak-type stress patterns are given for uniform bars under longitudinal impact which show the effects on the stress distribution produced by concentrated loads and by symmetrically placed circular holes. These experiments were conducted approximately five years ago and were reported in References 5 and 6, but these references are not readily available. In discussing this subject with other investigators, we found considerable interest in these experiments, and we were encouraged to publish the results even though they are preliminary in nature.

Experimental Results

The compression bars used in these experiments are listed in Table 1. Stress patterns of these models under longitudinal impact were photographed using the equipment and techniques described in Reference 2.

Uniform Load, Uniform Bar

Longitudinal impact between a uniform compression bar fixed at one end and struck uniformly by a heavy rigid mass at the other end was produced in the manner shown in Fig. 1. The hammer of the pendulum loading mechanism and the anvil were made of steel so that they may be considered as rigid relative to the plastic model. Several pro-

TABLE 1—COMPRESSION BARS USED

Model No.	Loading Condition	Geometry	Material	Length, in.	Depth, in.	Thickness, in.
I	Uniform	Uniform	Castolite	4.34	0.324	0.251
II	Uniform	Uniform	Bakelite	4.34	0.341	0.253
III	Concentrated	Uniform	Bakelite	4.34	0.350	0.242
IV	Uniform	Central circular hole, 0.194 in. diam.	Castolite	4.34	0.501	0.238

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Paper is based on research initially sponsored by the U. S. Navy Bureau of Yards and Docks, and subsequently taken over by the Office of Ordnance Research, U. S. Army.

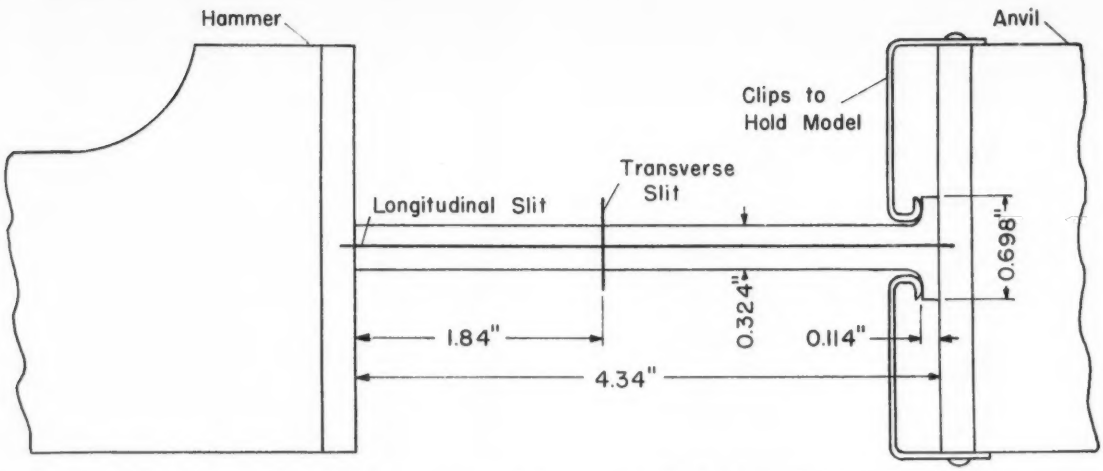

Fig. 1—Experimental setup for Model No. I showing impact of hammer, method of support and location of slits

cedures for holding the model against the anvil were tried. The design shown in Fig. 1 proved to be the most satisfactory and was used throughout this work.

Figure 2 gives the experimental stress patterns* obtained from Model No. I made of Castolite. It is seen that black and white rectangles were obtained from the transverse slit and isosceles triangles from the longitudinal slit. These results are in agreement with theoretical predictions as discussed in References 3, 5 and 6.

Similar results were obtained from Bakelite, as can be seen from Fig. 3 which gives the stress patterns obtained from Model No. II. A comparison of Figs. 2 (a) and 3 (a) shows that the alignment between the hammer and compression bar was not as good in the test with Bakelite as it was with Castolite. Nevertheless, the characteristic patterns of black and white rectangles and triangles are clearly evident in the Bakelite model.

Concentrated Load, Uniform Bar

In order to apply a concentrated load across the full thickness of the bar, a steel pin $^3/_8$-in. long and $^1/_8$-in. diam was attached to the face of the hammer, Fig. 1. The axis of the pin was made perpendicular to the plane of the bar, and the hammer and model were carefully aligned so as to produce axial loading and a plane state of stress. The concentrated load was applied to Model No. III (Bakelite), and the resulting dynamic photoelastic stress patterns are given in Fig. 4.

The symmetry of the stress patterns obtained from transverse slits, Figs. 4 (a, b, c, d), with respect to the longitudinal centerline of the bar shows that the

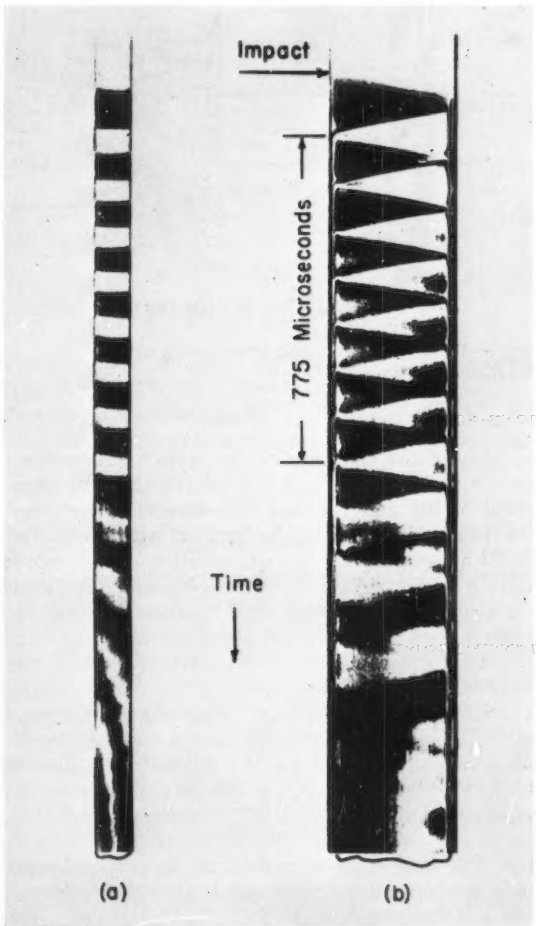

Fig. 2—Dynamic photoelastic stress patterns for Model No. I

(a) Transverse slit. (b) Longitudinal slit.

* *It should be noted that some of the details of the original stress patterns have been lost in the photographic reproduction of the composite illustrations such as Fig. 2. This is especially true with respect to the contrast in the transition region between white and black fringes. The comparisons of stress patterns which are made in this paper are based on an inspection of the original negatives.*

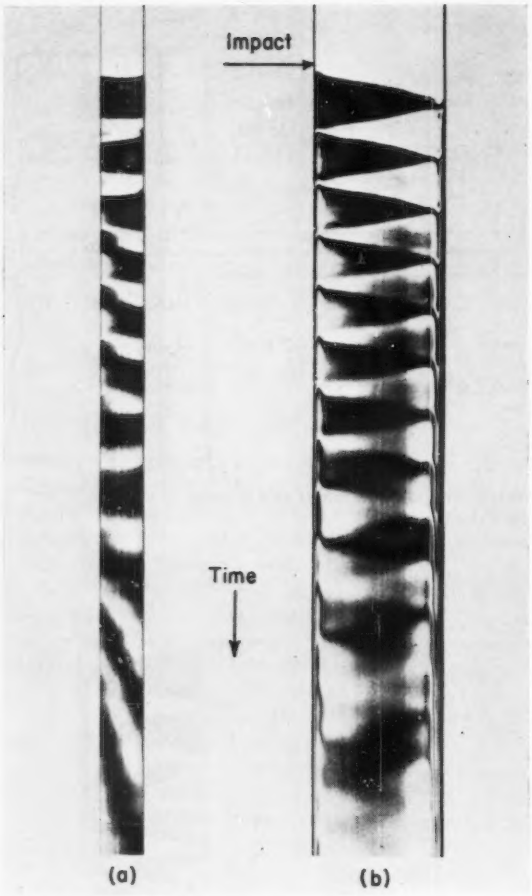

Fig. 3—Dynamic photoelastic stress patterns for Model No. II

(a) Transverse slit. (b) Longitudinal slit.

axiality of the load was nearly perfect. A comparison with Figs. 2 (a) and 3 (a) shows that the alignment of the uniform load was somewhat disturbed by the small rotation of the hammer which produced slight inequalities in the deformation of the model during impact, whereas the alignment of the concentrated load was maintained throughout the entire impact because the pin permitted a small rotation of the face of the hammer without disturbing the axiality of the load.

Inspection of Figs. 4 (c, d) shows that at distances of $^1/_2$ in. or more from the struck end, the stress distribution produced by the concentrated load is uniform across the depth of the bar. However, the gradual change from black to white to black rectangles (clearly seen on the negatives) indicates that the wave front is gradual and smooth, whereas in the uniformly distributed impact load, Fig. 3 (a), it is abrupt and steep.

Further information on the change in the wave front (dispersion) was obtained by using a longitudinal slit, Fig. 4 (e). When this pattern is

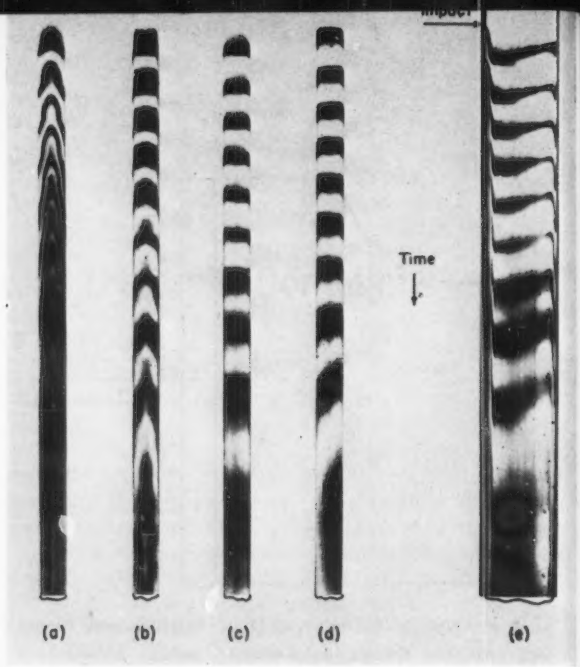

Fig. 4—Dynamic photoelastic stress patterns for Model No. III

(a) Transverse slit $^1/_4$ in. from concentrated load. (b) Transverse slit $^3/_8$ in. from concentrated load. (c) Transverse slit $^1/_2$ in. from concentrated load. (d) Transverse slit 2 in. from concentrated load. (e) Longitudinal slit.

compared with Fig. 3 (b), it is seen that the type of loading influences the stress-time history throughout the entire bar. However, for a given velocity of impact, it was found that the maximum fringe order, as well as the duration of impact, are nearly the same in a bar subjected to either a concentrated load or a uniform load.

Effect of a Circular Hole

Model No. IV (Castolite) contained a central, circular hole and was loaded uniformly as in Fig. 1. Successive tests were made with the transverse slit at various locations, and typical stress patterns are given in Fig. 5.

During the passage of the first stress wave and even after several reflections, a remarkable similarity is observed in the stress patterns which were obtained from transverse slits symmetrically placed with respect to the hole, Figs. 5 (a, c). The stress pattern through the center of the hole, Fig. 5 (b), does not have sufficient resolution to determine the maximum fringe order at the hole with accuracy. With improvements in technique, however, the method of streak photography could be used to determine dynamic factors of stress concentration.

From Fig. 5 (d), it is seen that the hole has very little effect on the stress distribution at a distance of $^{13}/_{16}$ in. from the edge of the hole. Although the shapes are rather distorted, the sharp contrast between the black and white rectangles in Fig. 5 (d) shows that the wave front is steep as in the uniform bar under uniform load, Fig. 2 (a). For the same velocity of impact, it was found that the

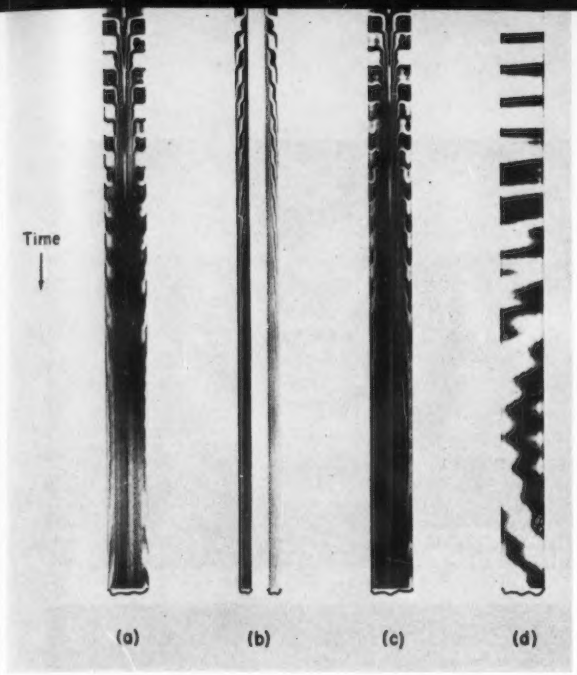

Fig. 5—Dynamic photoelastic stress patterns for Model No. IV

(a) Transverse slit, $^1/_{16}$ in. from edge of hole, hammer side. (b) Transverse slit through center of hole. (c) Transverse slit, $^1/_{16}$ in. from edge of hole, anvil side. (d) Transverse slit, $^{13}/_{16}$ in. from edge of hole, anvil side.

duration of impact as well as the maximum fringe order in regions away from the hole are nearly the same as in a bar without a hole.

Conclusion

The experiments described above are too limited in number and scope to warrant broad conclusions. They do, however, indicate trends which can tentatively be stated as follows:

1. For a given velocity of impact, the maximum stresses in the region of uniform distribution and the duration of impact, in a uniform bar supported and struck in the manner described, are not affected significantly by a concentrated load or a circular hole.

2. A concentrated load tends to produce dispersion in the wave front. The relatively steep and abrupt wave front which is developed when the impact is uniformly distributed over the end, is altered into one which is gradual and smooth. No such dispersion is produced by the hole. The influence of the discontinuity thus seems to depend on the type and severity of the discontinuity.

Further work is needed to explore this field, and such work is now in progress.

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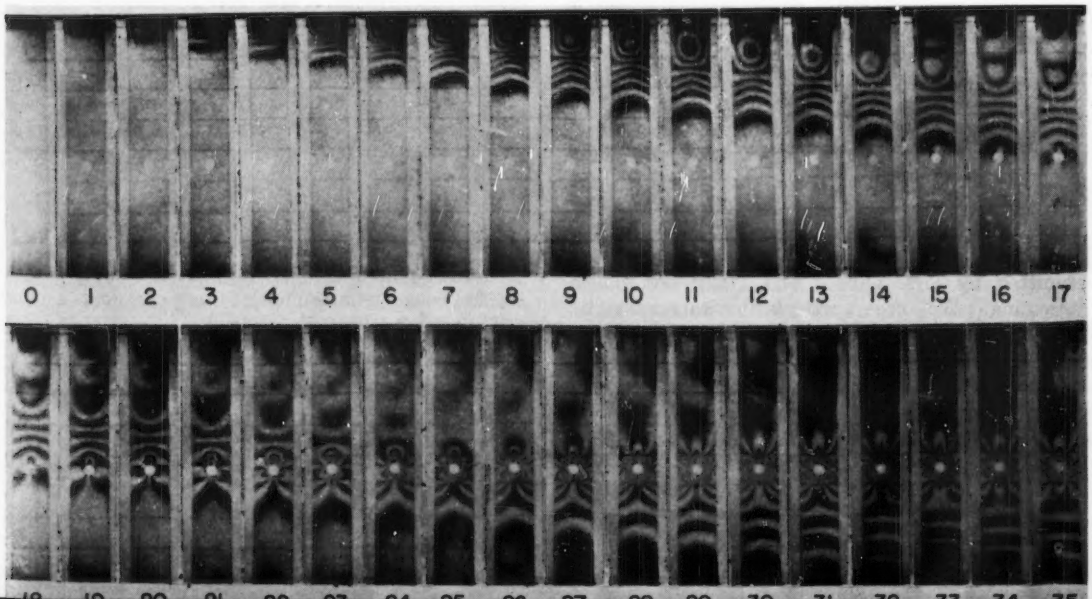
Discussion

By A. J. Durelli and J. W. Dally

The following remarks are made on the basis of several years' work in the area of dynamic photoelasticity by the discussers:

1. Figure D1 shows the dynamic fringe pattern

Fig. D1—Dynamic fringe patterns obtained by subjecting a Hysol 8705 strut with a central circular hole to an axial impact. (Photographs taken with a Fastax camera at about 13,000 frames/sec)



obtained by subjecting a Hysol 8705 strut with a central circular hole to axial loading, accomplished by dropping a flat-bottom weight squarely on the end of the strut. No lubrication was applied between the interface of the weight and the specimen. The following observations are made: (*a*) At impact very near time $t = 0$ (Frame No. 1) the first fringe (0.5 fringe order) is curved with the center portion leading the edges. (*b*) As the leading fringes propagate, they first straighten and then curve in the other direction with the edges leading the center. Likely, this change in curvature is due to a combination of frictional effects at the interface, viscoelastic dispersion and geometric dispersion. (*c*) When the leading fringes reach the hole, a complex fringe pattern is formed. The fringes reform after passing by the hole at a position 3 to 4 diameters below the hole, and propagate in much the same manner as they did before they reached the hole.† (*d*) The average velocities of the fringes as they pass through the neighborhood of the hole are the same as the velocity of the fringes before and after the hole. A given fringe order arrives at a given point on the strut at a given time whether there is a discontinuity present or not.

2. In the case of two-dimensional wave propagation which is illustrated in Fig. D2a, a fringe pattern is produced in a plate of Hysol 8705 by the explosion of a small charge of lead azide. The fringe reforms after the discontinuity as it continues to propagate.

3. The influence of the loading function is illustrated in Figs. D2b and D2c. In Fig. D2b, a point impact load is applied to a plate by a falling sphere which produces a rather long-duration pulse. In Fig. D2c, a point impact load is applied by a charge of lead azide which gives a total load duration of somewhat less than 10 μsec. The fringe patterns produced by these two point impact loads are strikingly different and clearly illustrate the dependence of the stress waves on the duration of the load.

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† *Durelli, A. J., and Dally, J. W., "Stress Concentration Factors Under Dynamic Loading Conditions," Journal Mechanical Engineering Science, Vol. 1, No. 1, 1959.*

Authors' Closure

The stress patterns on stress-wave propagation submitted by Drs. Durelli and Dally are indeed interesting. We are particularly impressed by Fig. D2a which may be described as "self-calibrating." It is hoped that the present paper, including the discussion, will throw light on the existence of a dynamic Saint Venant's principle and help to clarify and to formulate it.

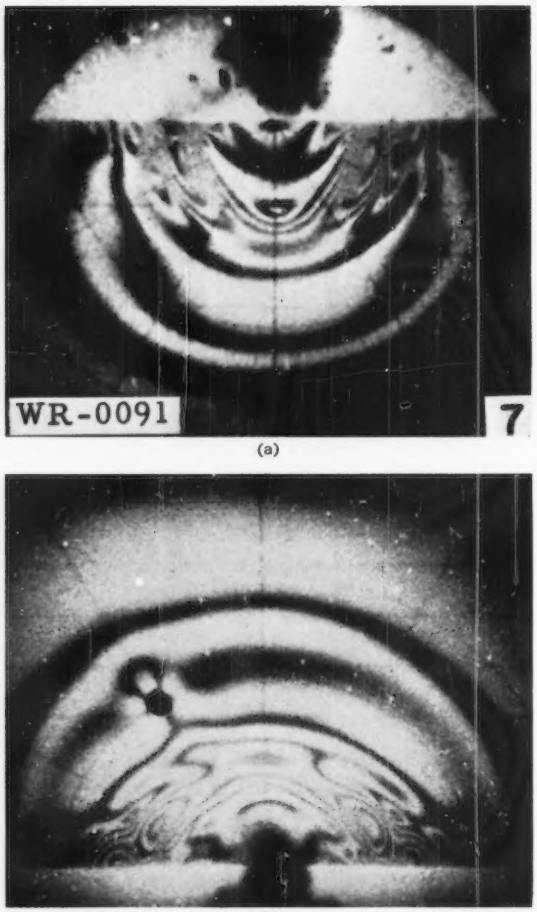

Fig. D2—Fringe patterns produced by a compressive stress wave in a large plate of Hysol 8705. (Photographs taken with a Fastax camera at about 6000 frames/sec)

(a) Plate with a rigid obstruction. Wave was produced by detonating a small lead-azide charge at the center of one edge of the plate.
(b) Wave produced by a falling steel sphere.
(c) Wave produced by a small lead-azide charge

Accuracy of Birefringent-coating Method for Coatings of Arbitrary Thickness

Authors endeavor to develop and verify rational concepts of the behavior of birefringent coatings, as a step toward general understanding of the factors that control accuracy of method

by Daniel Post and Felix Zandman

ABSTRACT—Rational concepts of the behavior of birefringent coatings are developed for both plane-stress problems and general surface-strain problems. For plane stress in elastic bodies, accuracy of stress or strain determinations along free boundaries is almost entirely independent of coating thickness; however, where Poisson's ratios of coating and structure are unequal, the state of stress in the structure might be influenced by the presence of the coating. In experimental investigations of four geometrical discontinuities with coating thicknesses up to 0.9 in. and materials of unequal Poisson's ratios, no influence of coating thickness on boundary strains was observed. For some three-dimensional problems, local shear tractions developed at the interface introduce a dependence upon coating thickness, but the resultant error in strain determinations was approximately 5% for a case studied experimentally. Strain distributions on singly and multiply connected surfaces in two- or three-dimensional bodies can be studied effectively by the method of birefringent-coating measurements.

Introduction

The birefringent-coating method of experimental stress analysis is a logical extension of conventional photoelastic methods. The stress-optical or strain-optical behavior of the birefringent-coating material and the techniques for measuring birefringence are identical to those already well established for photoelasticity. The two methods differ only by the manner in which the state of stress is developed in the birefringent material. This difference is most significant, however, since it plays a primary role in the formulation of concepts pertaining to birefringent coatings, particularly in regard to accuracy of analyses in which thick coatings are used.

The basic concept of the birefringent-coating method is generally credited to Mesnager[1] (1930). The first reports describing successful applications of the method began to appear in 1953 in France.[2] Interest has intensified in recent years, both in academic and industrial circles, as experimental techniques have advanced and theoretical considerations have matured. A growing confidence in the method has developed as a result of many favorable comparisons between results of birefringent-coating measurements and electric-strain-gage or photoelastic measurements. On the other hand, the accuracy of birefringent-coating measurements near geometrical discontinuities (notches, etc.) and other cases of substantial strain gradients has been the subject of some controversy, which is further stimulating activity in the area.

In this article, the authors endeavor to develop rational concepts of the behavior of birefringent coatings, as a step toward general understanding of the factors that control accuracy of the method. In addition, experimental analyses were undertaken to verify some of these concepts and to gain further insight into the nature of coating behavior.

Plane-stress Problems

Basic Concepts

Birefringent coatings are elastic bodies bonded to surfaces of other deformable bodies (hereafter called structures or structural parts). In general, forces must be transferred from the structure to the coating by shear forces developed at the interface; however, the state of stress or strain at a point in the coating depends upon the continuity of this elastic member as well as upon the shear tractions.

Concepts of coating deformation for plane-stress problems will be developed by considering the transfer of forces to thin coatings and, subsequently, these concepts will be extended to coatings of arbitrary thickness. The presentation will be restricted in this section to problems in which the structure and

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Paper presented at 1959 SESA Spring Meeting held in Washington, D. C., on May 20–22.

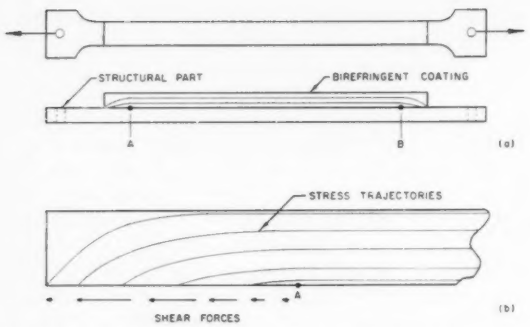

Fig. 1—Transfer of forces from structure to coating

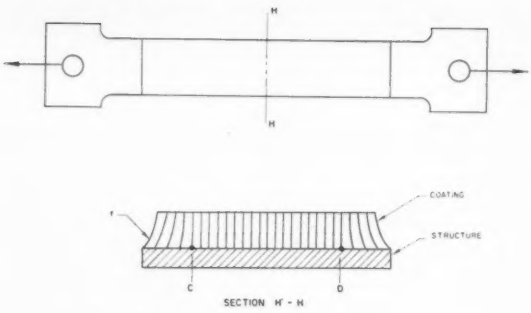

Fig. 3—Poisson contraction for thin coating

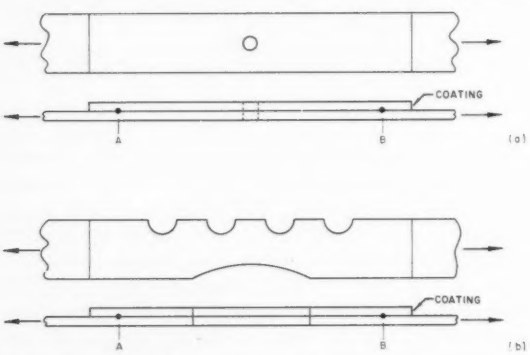

Fig. 2—Examples of discontinuities in plane-stress problems

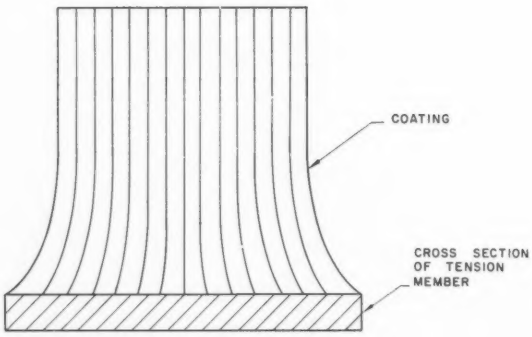

Fig. 4—Poisson contraction for thick coating

coating have equal values of Poisson's ratio. The first structural part to be considered is a simple elastic tension member, as shown in Fig. 1a. Stress trajectories through the thickness of the coating are approximately as drawn in the side view of the coating and in the enlarged view of Fig. 1b. The deformation of the coating is introduced by the action of shear forces near the ends of the coating. A concentration of shear stress is developed near the discontinuity of the coating layer. This is a local concentration, however, and shears diminish to zero a small distance from the discontinuity. The sections at which the shear tractions vanish are designated A and B in Fig. 1. Within zone AB, both the structure and coating are in a state of plane stress. The birefringent coating behaves exactly as an independent member in pure tension, subjected to the same end conditions, or displacement, as the portion of structural member in this zone. The deformation between sections A and B must be identical for the structure and coating, and significantly, this is true even if the coating is not bonded in this zone. An important class of problems, namely the case of zero-shear tractions at the coating interface, is established here.

Next, consider the case of the same tension member, but with any variety of discontinuities introduced into zone AB, as depicted in Fig. 2. The structure and coating within this zone are still subjected to equal end displacements since the load carried by the coating is completely transferred in the border zone outside A and B. It is well known that stress and strain distributions in elastic bodies depend only upon geometry and loading conditions. Consequently, if two bodies of equal geometry are given identical boundary displacements, the displacements and strains at corresponding points throughout the bodies will be identical. Therefore, the deformations of structure and coating are equal throughout zone AB, and no shear tractions are required to maintain continuity at the bonded interface. Since the birefringence developed in the coating does not depend upon a bond at the interface, the coating behaves exactly as a separate photoelastic model of the structure subjected to the same end displacements. Thus, for the case of geometrical discontinuities, there is no disparity between stresses or strains developed in the structure and coating that would not occur in conventional photoelasticity between stresses or strains developed in the prototype and model.

A necessary condition for zero shear tractions is that the structure and coating have identical geometry (in two dimensions). This precludes identical strain distributions in the zone outside AB, for there the coating is discontinuous, whereas the structure is

continuous. This region of local shear tractions extends over a section of length only a few times the thickness of the coating, the factor depending upon the ratio of moduli of elasticity of the two materials. The bond must have high efficiency in this border region, but a poorer bond or no bond at all would suffice elsewhere.

Effect of Poisson's Ratio

An underlying assumption required for the development of identical deformation of the structure and coating is that Poisson's ratios for the two materials are the same. In practice, however, the values may be slightly different. Consequently, if the structure and coating are unbonded, but subjected to identical end displacements, the deformations or strain distributions will be somewhat different. If the coating is bonded, the strains in structure and coating will be identical at the interface. However, there will be a tendency for the upper layers of the coating to assume the state of deformation of the equivalent unbonded coating, and a transition between conditions of bonded and unbonded coatings will develop through the coating thickness.

Pertinent features of coating behavior are illustrated in Fig. 3 for a structural part in pure tension. Deformation of the cross section of the member is shown greatly exaggerated for the case in which Poisson's ratio of the coating exceeds that of the structure. Lines drawn in the coating represent initially straight, parallel lines in the unstressed member. If the coating is thin or the structure is wide, continuity conditions preclude a strain gradient through the coating thickness in the central region CD. (However, transverse constraints vanish at the free edge and transverse deformation ensues.) At the interface, and everywhere within zone CD, the coating assumes the deformation of the structure. Birefringence measurements taken at normal incidence in zone CD will yield a birefringence, N, proportional to the difference between longitudinal strain ϵ_1 and transverse strain ϵ_2 in the structure. Here the transverse strain is equal to $-\nu_s\epsilon_1$; therefore

$$N = 2tK(\epsilon_1 - \epsilon_2) = 2tK(1 + \nu_s)\epsilon_1 \qquad (1)$$

where ν_s is Poisson's ratio for the structure, t is coating thickness and K is the strain-optical coefficient of the coating material.

In contrast, the coating material immediately adjacent to the free edge (Fig. 3) is totally unrestrained and is free to develop its normal Poisson contraction. As a result, the transverse strain for each element along the edge is $-\nu_c\epsilon_1$, where ν_c is Poisson's ratio of the coating. The birefringence developed here is

$$N = 2tK(\epsilon_1 - \epsilon_2) = 2tK(1 + \nu_c)\epsilon_1 \qquad (2)$$

The values computed from eqs 1 and 2 are ordinarily nearly equal, the deviation amounting to $(\nu_s - \nu_c)/(1 + \nu_s)$.

Exact prediction of coating behavior for a boundary point in a general plane-stress system presents a complex three-dimensional elasticity problem. However, it may be inferred that eq (2) should apply with good accuracy for any boundary point. This inference is based upon knowledge that the coating will not experience a large change in shape relative to the structure. In contrast to the case of transverse displacement, displacement in a direction tangent to a boundary point is restrained by the action of the continuous elastic medium comprising the boundary surface. Accordingly, the principal strains parallel to the boundary are expected to remain substantially constant throughout the coating thickness and equal to ϵ_1, where ϵ_1 is now defined as the tangential strain at a boundary point in the structure. In the coating, normal strain at the boundary would remain $-\nu_c\epsilon_1$, and birefringence would be governed by eq (2) for all boundary points. The validity of this inference was corroborated in the course of experimental investigations reported in a subsequent section.

The birefringent-coating method is equally applicable to multiply connected bodies, since the basic deformation of the coating is that of the structure. In experimental analyses that require models of multiply connected bodies with nonequilibrated boundary loads, substantial errors can result when Poisson's ratios for model and prototype are not equal; it is shown, however, that errors are generally not large in regions of high stress.[3] Consequently, potential accuracy of the birefringent-coating method might reasonably be considered superior to that of the photoelastic method for such problems.

The effect of Poisson's ratio for the case of a very thick coating is illustrated in Fig. 4 by the deformation of the cross section of a coated tension member. Lines in the coating represent initially straight lines in the unstressed member. If the coating is adequately thick or the structure adequately narrow, constraints at the interface will influence a relatively small thickness of material, and the normal Poisson contraction will develop throughout most of the coating thickness. Consequently, eq (2) should be applied for every point in this member, instead of at boundary points alone. Similarly, the integrated birefringence through a very thick coating remains essentially independent of the interface tractions for any singly connected body in plane stress.

Effect of Coating Thickness

The effect of coating thickness will be developed on the basis of equal Poisson's ratios of structure and coating, and any influence arising from dissimilar values of the ratio can be superimposed upon the results afterward. For structures in a state of plane stress, the coating behaves essentially as an independent member subjected to given end displacements. In regions remote from discontinuities, thick coatings can be treated as two-dimensional problems, and birefringence measured at normal incidence to the interface exhibits the same distribution as developed with thin coatings. In regions of

discontinuities, however, three-dimensional stress solutions are required to predict birefringence of thick coatings.

In the present approach, the analytical solution for the three-dimensional stress distribution around a hole in a tensile plate, by Sternberg and Sadowsky,[4] will be interpreted in terms of thick-coating behavior. Subsequently, other discontinuities will be treated experimentally. The analyses will be confined to the evaluation of peak stresses or strains by the birefringent-coating method.

The Sternberg-Sadowsky problem is depicted in Fig. 5. A hole of radius R lies in an infinite plate of thickness $2c$, the axis of the hole being perpendicular to the bounding surfaces of the plate. While the loading conditions for the Sternberg-Sadowsky problem were more general, only the case of uniaxial tension parallel to the x-axis will be considered here; specifically, $\sigma_x = \sigma$ at infinity. Maximum stresses occur along lines $x = 0, y = \pm R$; these maxima are normal stresses acting in the x-direction. For pure plane-stress conditions (c approaching 0), $\sigma_{max} = 3\sigma$. For plates of finite thickness, $\sigma_{x(x=0,\ y=R)}$ varies with z; the average value of this stress through the thickness of the member is always equal to 3σ, and its variation with z is indicated in Fig. 6 for a wide range of plate thicknesses. Regardless of the thickness ratio, $\sigma_{x(x=0,\ y=R)}$ is less than 3σ at the plate boundaries ($z/c = 1$) by an amount that never exceeds 10% of 3σ, whereas it is greater than 3σ in the interior by an amount that never exceeds 3% of 3σ. Significantly, the stress correction is 0 in the central portion of the plate (z/c near 0) for thick plates (large c/R).

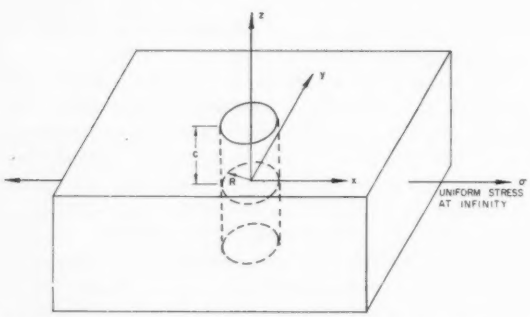

Fig. 5—Coordinates for Sternberg-Sadowsky problem

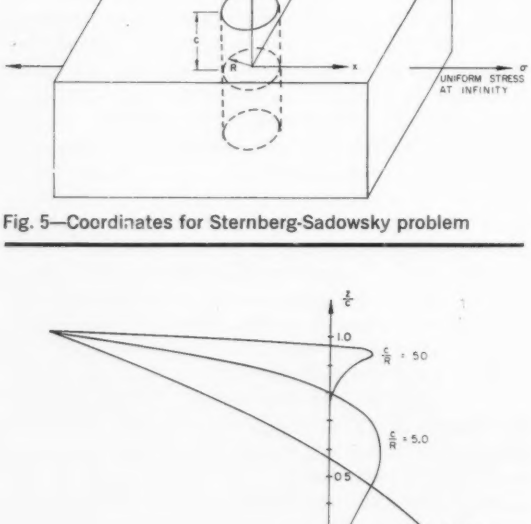

Fig. 6—Stress correction factor versus z/c

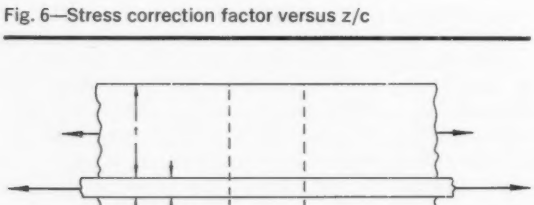

Fig. 7—Structure and birefringent coatings of arbitrary thickness with circular hole

Returning to the question of birefringent-coating measurements, consider the case where the structural part is a large plate in uniform tension having a central hole whose radius is small compared to the dimensions of the plate, but large compared to the plate thickness. Figure 7 shows the part with birefringent coatings of arbitrary thickness, t, bonded to both faces. Two equal coatings are employed here to maintain symmetry and thereby eliminate any question of bending action. Normal incidence birefringence measurements at the point of stress concentration ($x = 0, y = R$) are sensitive to the integrated values of $\sigma_x - \sigma_y$ through the coating thickness. Since σ_y is 0 along the free surface of the hole, birefringence is directly proportional to the integrated value of σ_x.

For practical purposes, the coating may be assumed to behave as half the infinite plate considered above (from $z = 0$ to $z = c$), in which case the integrated value of $\sigma_{x(x=0,\ y=R)}$ is exactly 3σ. Small deviations from this condition arise as follows. (1) The structural part has finite thickness, and strains at its free surfaces depart slightly from those prescribed by conditions of pure plane stress. However, the correction of Fig. 6 is small compared to 10% except for very large thickness ratios (which are outside the realm of plane-stress problems) and deviations of interface strains are correspondingly small. Strain distributions determined by the birefringent-coating method will fall between those corresponding to the plane-stress condition and the actual interface condition. The deviation is extremely small. (2) The interface does not remain plane, but rather deforms in the pattern of the free surface of the uncoated structure. Since the stress corrections of Fig. 6 are small, this deformation is practically identical to that of an equivalent plane within a thicker plate. Deformation of the coating corresponds to the deformation of a corresponding outer layer in a homogeneous plate of total thickness $(2t + 2c_1)$. Accordingly, the birefringence should be integrated through a thickness $z = t + c_1$ to $z = c_1$. Figure 6 shows that this integration yields exactly

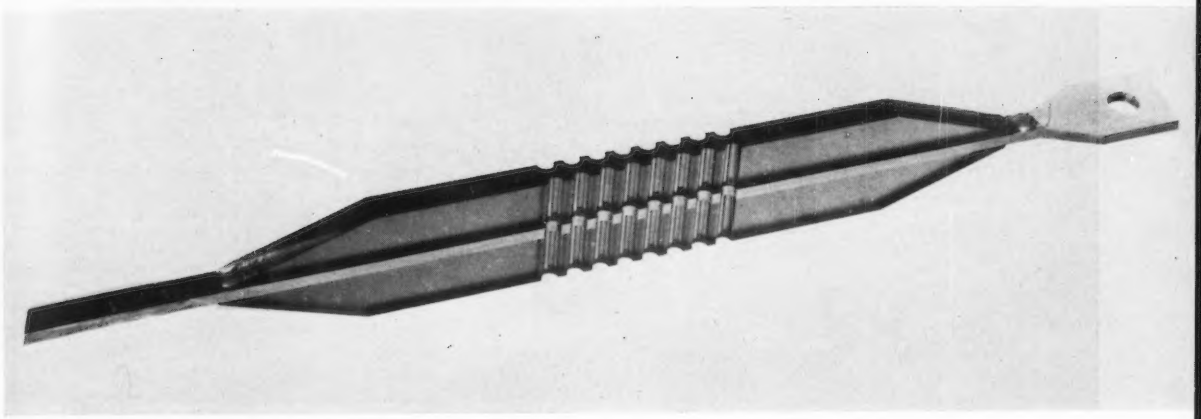

Fig. 8—Multiply notched specimen with thick birefringent coatings

the plane-stress value for large coating thicknesses, whereas slight deviations from the plane-stress value occur for small coating thicknesses. These deviations are very slight since the maximum corrections are themselves small.

All departures from precise plane-stress conditions may be thought to stem from the presence of a third stress, σ_z, developed along the boundary of the hole. Sternberg and Sadowsky show that this triaxiality diminishes rapidly with distance from the hole and a biaxial state of stress is nearly achieved at a distance of one hole diameter from the boundary for any plate thickness. Visualization of the role of σ_z in the case of a hole leads to the prediction of stress behavior for other discontinuities. Specifically, it is conjectured here that triaxiality has negligible influence on normal stresses parallel to the boundary planes for all two-dimensional geometrical discontinuities. This generalization was investigated experimentally for a few discontinuities and results are reported in a following section.

Experimental Verifications

Unbonded Coatings

The correspondence between birefringence distributions in bonded and unbonded coatings was investigated by means of the multiply notched specimen pictured in Fig. 8. The structural part was aluminum alloy 2024-T4, machined to 0.178 in. thickness. Birefringent coatings of 0.750 in. thickness, symmetrically located on each side of the structure, were made of a photoelastic plastic, Kriston*. An array of semicircular notches of $^1/_8$ in. radius, $^3/_8$ in. between centers, and $^3/_{16}$ in. minimum width was introduced in the composite member as shown. Flat mirror-like surfaces were polished into the aluminum member in the vicinity of the notches. Before bonding, a silicone grease was applied to one portion of the polished surface to assure that the section remained unbonded.

* *Kriston was formerly manufactured by the B. F. Goodrich Company. This material is no longer commercially available.*

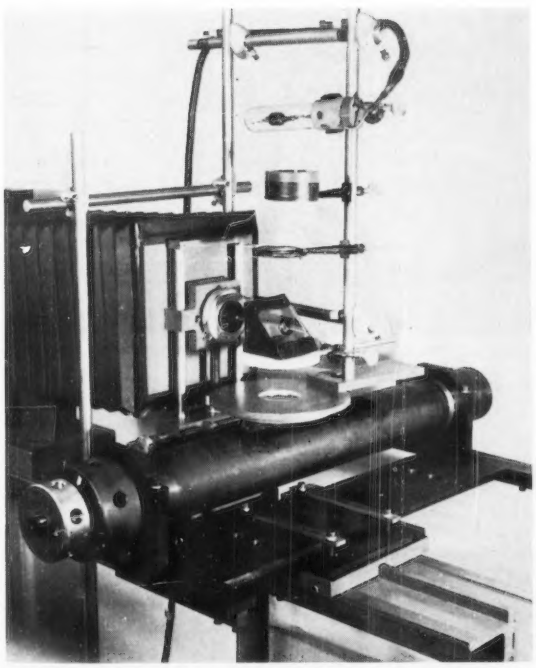

Fig. 9—Reflection polariscope with loading fixture for multiply notched specimen. The optical train, part of which is not visible, consists of a light source, condensing lens, aperture plate, semitransparent mirror, collimating lens, polarizer, quarter-wave plate, model, monochromatic filter and camera

Experimental apparatus consisted of the reflection polariscope and loading fixture shown in Fig. 9. The specimen was mounted between ball and socket joints in the fixture, and loaded by means of a fine-pitch screw. The polariscope produced a collimated beam of circularly polarized monochromatic light (λ5461), normally incident upon the specimen.

The birefringence pattern is shown in Fig. 10. The high-fringe orders attained here permit immediate comparison of patterns in the bonded zone (left of scribed line) and the unbonded zone (right of line). The patterns in both zones are identical,

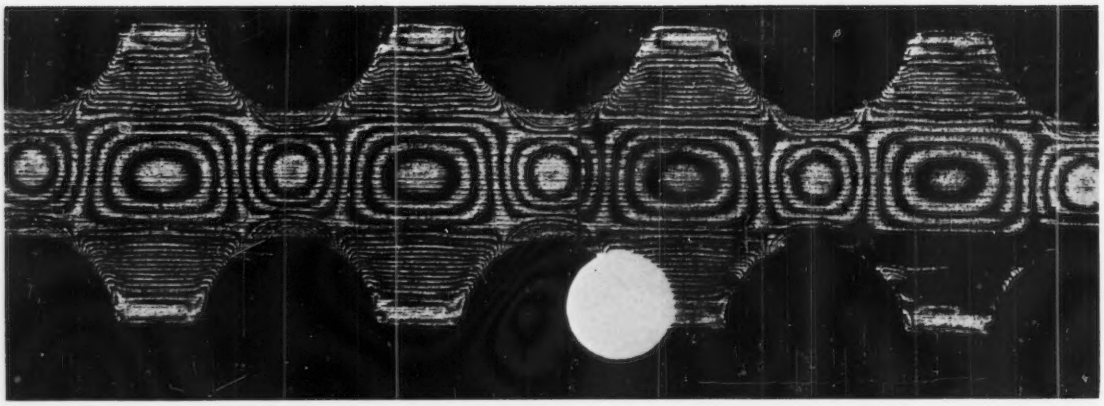

Fig. 10—Birefringence exhibited by multiply notched specimen of Fig. 8; observe equal distributions in bonded (left) and unbonded (right) sections

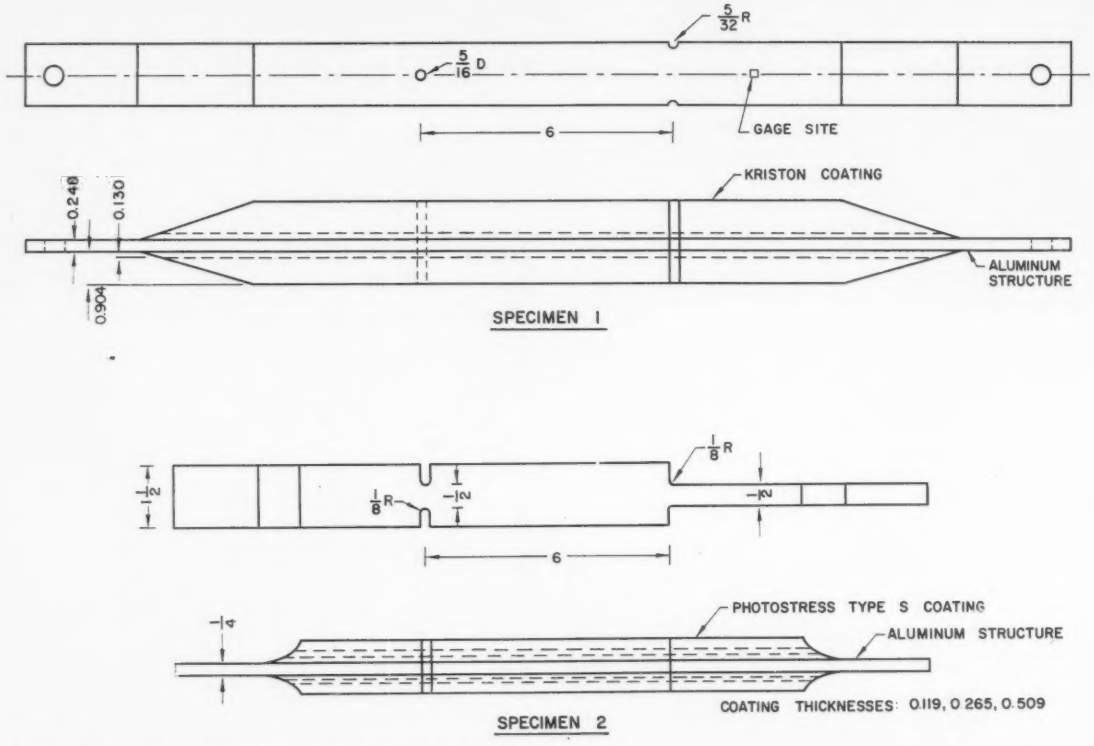

Fig. 11—Specimens for investigation of influence of coating thickness

and the correspondence between bonded and unbonded coatings is thereby confirmed for thick coatings and singly connected structures.

Validity of Measurements at Geometrical Discontinuities

Experimental Techniques. The correspondence between birefringence developed in thick and thin coatings was investigated for four geometrical discontinuities, namely, the circular hole, semicircular notch, deep notch and fillet. Drawings of the specimens are shown in Fig. 11. Measurements were taken at the discontinuities in both members for coating thicknesses shown by the dashed lines in the drawings.

The loading fixture used previously for the multiply notched bar was also employed for Specimen 1. Strains were measured at the interface by means of foil-type electric-resistance strain gages laminated between the structure and coatings. The optical system employed for this investigation is shown in

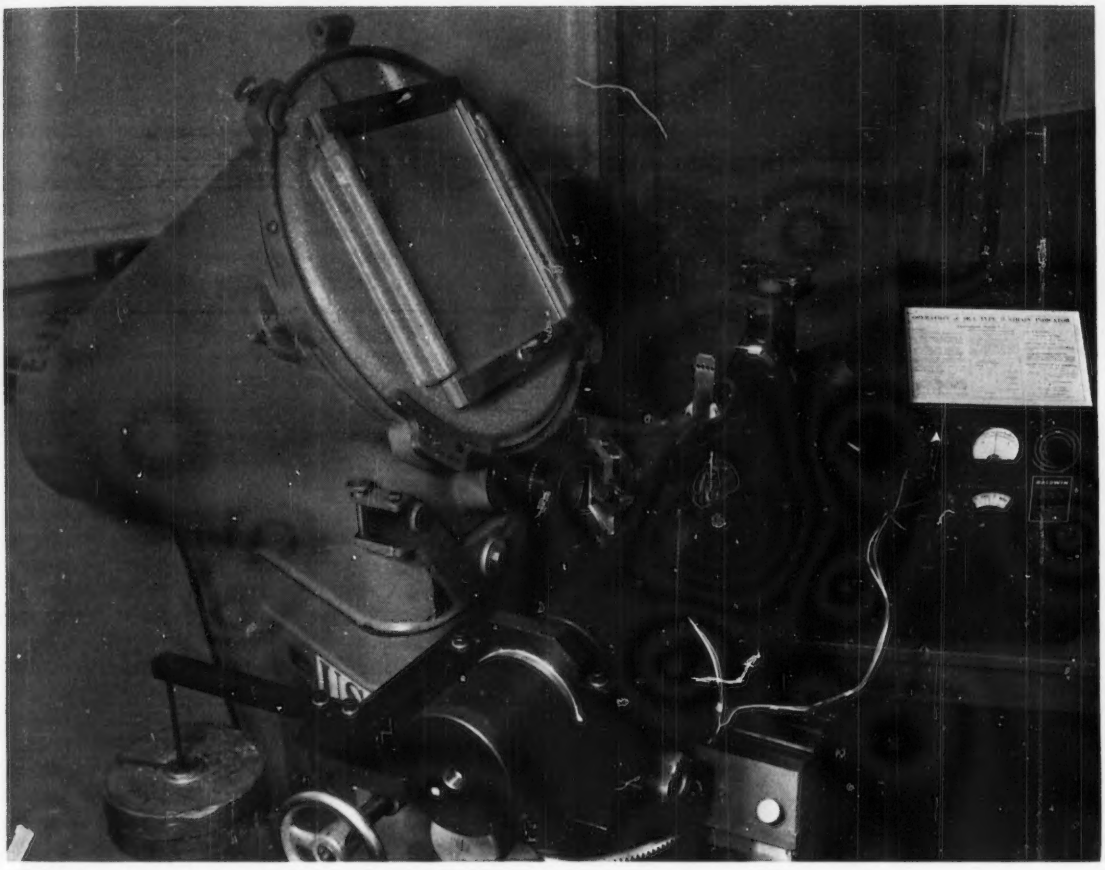

Fig. 12—Experimental apparatus for Specimen 1, Fig. 11

Fig. 12, together with the loading fixture. The basic structure is a commercial optical comparator (also called shadowgraph); the comparator was modified to function as a reflection polariscope by addition of the illumination system located behind the loading fixture. A collimated beam of monochromatic light (λ5461) was directed into the birefringent coating by an inclined semitransparent mirror. The polished surface of the aluminum structure reflected light back through the coating and partial mirror and into the objective lens of the comparator. A polarizer and quarter-wave plate was located in front of the specimen to provide circular polarization.

For measurements with the thick coating (0.904 in.), the fringe patterns in the neighborhood of the hole and the semicircular notches were photographed for no-load and full-load conditions. A representative pattern is shown in Fig. 13 for the full-load condition. The fringes are clearly defined and an accurate fringe count was possible. Initial birefringence near the discontinuities had principal axes parallel to the boundaries, and correction was made by simple subtraction of no-load and full-load fringe orders.

The coatings were subsequently reduced in thick-

Fig. 13—Birefringence pattern around hole in tensile bar; birefringent-coating thickness, 0.904 in.

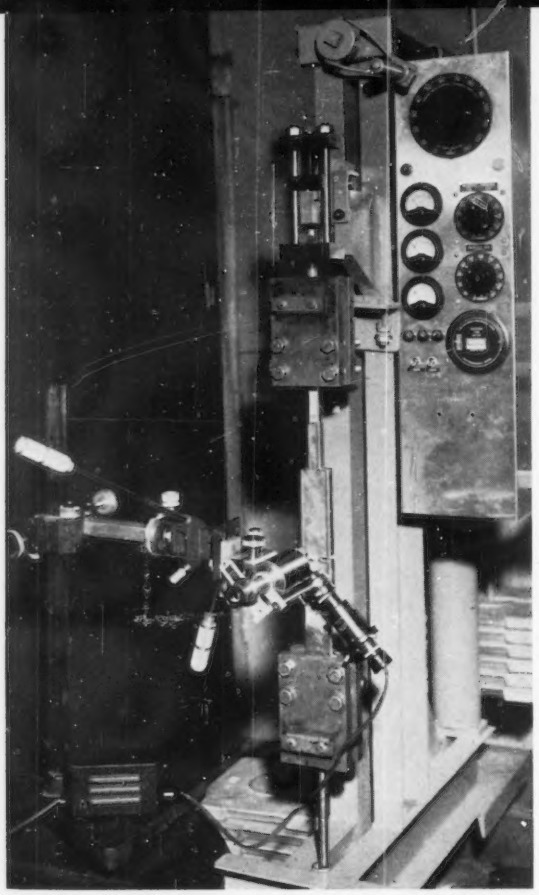

Fig. 14—Experimental apparatus for Specimen 2, Fig. 11

ness to 0.130 in. Increased sensitivity of measurements was required since birefringence diminishes with coating thickness; hence a Babinet-Soleil compensator was employed to measure fringe orders. No-load and full-load measurements were taken and the results were corrected for initial birefringence.

The experimental apparatus employed with Specimen 2 is shown in Fig. 14. The loading system was a lever-type deadweight device. Coating thickness was increased for successive tests by applying successive layers of $^1/_8$-in. thick Photostress Type S plastic sheets. In each test, the specimen was carefully aligned for pure tensile loading while viewing the birefringence pattern in a large field diffuse-light reflection polariscope. Measurements of maximum fringe order were made at the fillets and deep notches by means of a microscope-type reflection polariscope fitted with a Babinet compensator. At each discontinuity in the specimen, readings were taken for several load increments and the fringe order per unit load was determined from graphs of these measurements. Corrections were applied for the load carried by the coatings, and average longitudinal strains across the $1^1/_2$-in. wide section of the specimen were computed for Table 1. Loads carried by the structure were computed by the relation

$$F_0 = F_s \left[1 + \frac{t_c E_c (1 + \nu_s)}{t_s E_s (1 + \nu_c)} \right] \qquad (3)$$

where F_0 is applied force, F_s is force carried by structure, t_c, t_s are total thickness of coating material and structural material, respectively, E_c, E_s are modulus of elasticity for coating and structure and ν_c, ν_s are Poisson's ratio for coating and structure. Equation

TABLE 1—EFFECT OF COATING THICKNESS ON BIREFRINGENCE

Discontinuity	t/R	$\epsilon_{x(s)}$ μin./in.	$\frac{N_{max}}{t\epsilon_{x(s)}} \times 10^{-4}$	Maximum Deviation of $N_{max}/t\epsilon_{x(s)}$, %
Hole	0.83	1201	3.65	
Hole	5.78	613	3.67	0.6
Semicircular notch	0.83	1242	3.77	
Semicircular notch	5.78	615	3.73	1.1
Deep notch	0.95	243	6.04	
Deep notch	2.13	186	5.97	
Deep notch	4.07	87	6.13	2.7
Fillet	0.95	243	5.61	
Fillet	2.13	1186	5.64	
Fillet	4.07	87	5.68	1.2

Note: $N_{max}/t\epsilon_{x(s)}$ is given in units of fringes per inch thickness of coating, per unit longitudinal strain developed at the interface at a point remote from the discontinuity.

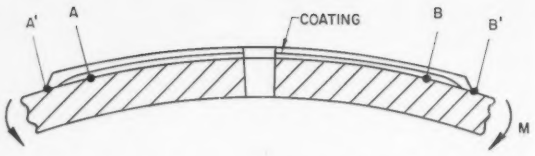

Fig. 15—Example of a three-dimensional problem with zero shear tractions in zone AB

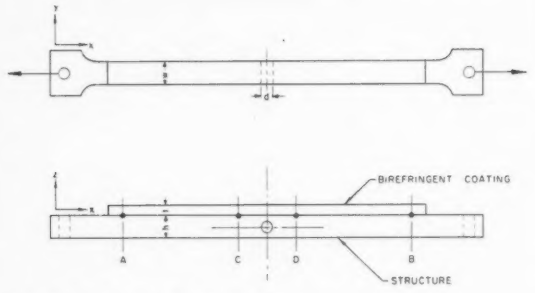

Fig. 16—Example of a three-dimensional problem in which shear tractions are not zero in zone CD

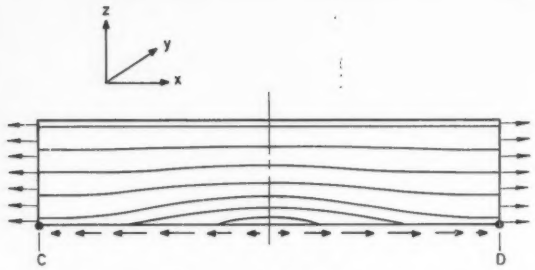

Fig. 17—Forces and stress trajectories in coating near hole

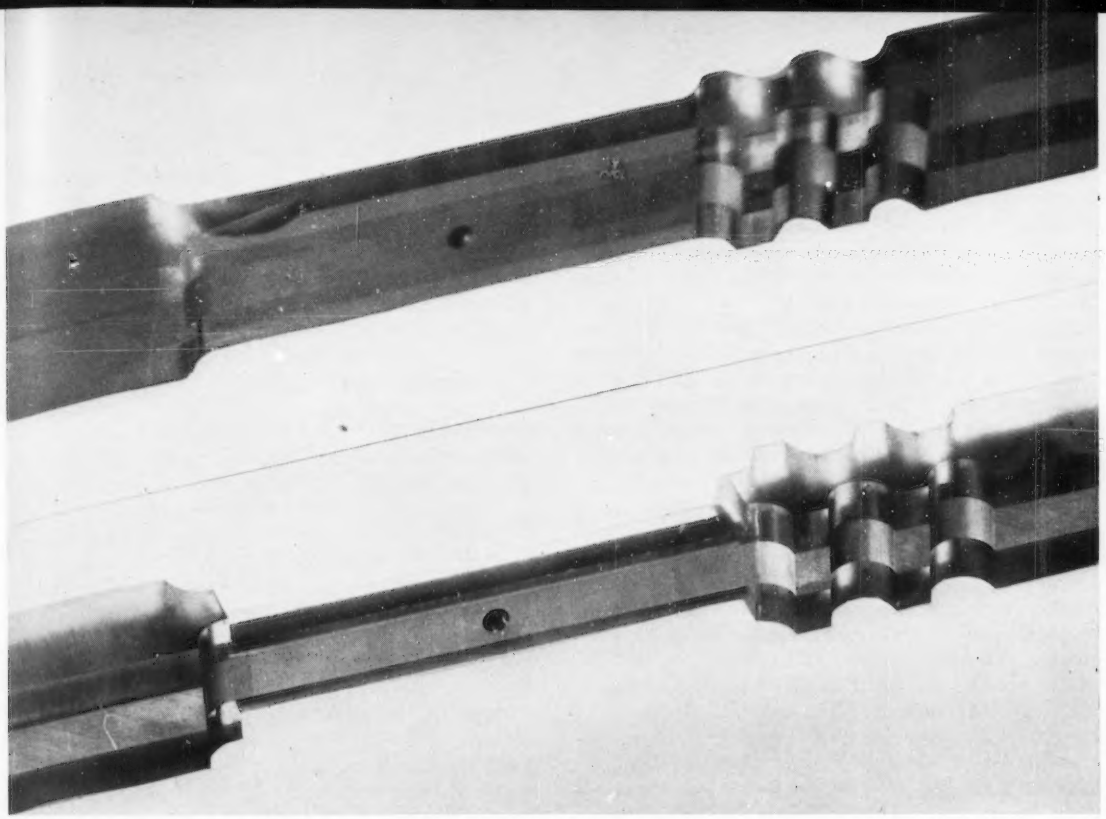

Fig. 18—Tension specimen with transverse hole. Coating thickness: top, 0.162 in.; bottom, 0.054 in.

(3) can be derived readily from consideration of the equilibrium of two elastic bodies subjected to the same end displacements. The elastic constants of E and ν were measured for both materials by means of electric-resistance strain gages.

Results

Careful determinations of maximum birefringence at the boundaries yielded the results presented in Table 1. The influence of coating thickness may be determined by variations of $N_{max}/t\epsilon_{x(s)}$ with thickness, where N_{max} is the maximum fringe order developed along the boundary of the discontinuity, t is thickness of coating and $\epsilon_{x(s)}$ is the longitudinal strain developed at the interface at a point remote from the discontinuity. The experimental analyses show that no variations exist within the limits of small experimental errors in each case. The remarkable consistency of these values for wide ranges of coating thicknesses provides strong corroboration of the conjecture stated above, namely, that the accuracy of birefringent-coating measurements of boundary stresses or strains is *independent of coating thickness* for plane-stress conditions.

It is significant to realize that these results verify the independence of coating thickness for two factors: (1) triaxiality of the stress system developed at geometrical discontinuities, as treated by Sternberg and Sadowsky for the case of circular hole, and (2) unequal values of Poisson's ratio for structure and coating. Factor (1) was verified independently by the results obtained from Specimen 1, since Poisson's ratios of the structure and the coating were nearly identical (0.325 and 0.32, respectively). Both factors were present in Specimen 2, since in that case Poisson's ratios for the structure and the coating, Photostress Type S, were 0.29 and 0.36, respectively.

General Surface-strain Problems

The concepts introduced above also apply to a large class of structures having three-dimensional geometry and loading conditions. An example is shown in Fig. 15, where an initially straight or moderately curved plate is subjected to either simple or compound pure bending. As before, no shear tractions are developed at the interface within zone AB; the deformation of the coating is controlled by forces introduced in the border zones (A′A and BB′) and by forces normal to the interface within region AB. The coating behaves basically like a surface slice taken from a three-dimensional photoelastic model. Birefringence measurements at normal incidence are independent of stresses perpendicular to the interface, but are determined by the integrated value of the difference of principal strains $(\epsilon_1 - \epsilon_2)$ acting in planes parallel to the interface. Since $\epsilon_1 - \epsilon_2$ varies linearly through the coating, corrections which relate integrated birefringence to interface strain can be derived readily, and no unknowns are introduced.

In cases where the surface strains depend upon factors other than geometrical discontinuities in the surface, bonded and unbonded coatings yield differ-

ent results. For example, consider the case of a transverse hole in a tension member, as depicted in Fig. 16. The displacements at sections A and B are identical for structure and coating. However, now there is a local concentration of strain near the central hole in the structure which would not be transferred to the continuous coating if it were unbonded. Accordingly, the deformation of the coating in this region is developed, in part, by the action of shear tractions at the interface. The forces acting on the coating in the affected region, zone CD, are shown schematically in Fig. 17, together with the stress trajectories developed for such a case. Obviously, the state of stress and strain is not independent of the z-coordinate, and the birefringence developed varies through the thickness of the coating.

This case was investigated experimentally to determine the effect of departure from plane-stress conditions. The specimen is shown in Fig. 18; with reference to the symbols shown in Fig. 16, the specimen dimensions are $h = 0.178$ in., $w = 0.185$ in., $d = 0.094$ in. and $t = 0.162$ and 0.054 in. for thick and thin coatings. The structure was 2024-T4 aluminum and the coatings were Kriston photoelastic plastic. The experimental apparatus was that shown in Fig. 12. Birefringence measurements were made at normal incidence to the interface for no-load and full-load conditions by means of a Babinet-Soleil compensator; measurements were taken at the section of symmetry and at successive points 0.100 in. apart. The load carried by the composite member was measured by means of electric-resistance strain gages.

The coatings carried a portion of the total load, thereby reinforcing the structure. The force F_c carried by the coatings could be calculated from the birefringence measurements if it is assumed that σ_y is 0. Thus

$$F_c = \frac{E_c A_c}{2tK(1 + \nu_c)} N \qquad (4)$$

where A_c is the total cross-sectional area of the coatings. Equation (4) was accepted as a good approximation of the reinforcement developed at any section. The remaining force carried by the structure was $F_s = F_0 - F_c$, where F_0 is the total force applied to the composite member.

Comparisons of birefringence developed at a section along the coating should be performed under the condition of equal values of F_s in the specimens being compared. Accordingly, F_s was calculated by the method indicated above for each data point and was employed in comparing the birefringence developed in the thick and thin coatings.

The results are presented in Fig. 19 on the basis of birefringence per unit thickness, per unit force carried by the structure at the cross section under consideration. The familiar lobes developed in the stress or strain distribution along the edge of a tensile bar with a central hole appear here. However, the measurements are sensitive to the thickness of birefringent coating, with differences of about 5% occurring in this case. Presumably, a coating of thickness approaching 0 would yield a slightly higher lobe in the graph, corresponding to a larger stress or strain on the surface of the structural part.

The explanation of this result appears to lie largely in the local reinforcement of the structure. It is surmised that birefringent coatings of moderate thickness actually measure interface strains with good accuracy, but that the presence of the bonded coating reduces the magnitude of strains that would otherwise occur along the surface. Perhaps this effect is obvious from Fig. 17, for the shear tractions acting on the coating are accompanied by equal and opposite tractions on the surface of the structural part which oppose the development of ϵ_z.

In addition to local reinforcement, the variation of $\epsilon_x - \epsilon_y$ through the thickness of the coating becomes important for thick coatings. The shear tractions developed at the interface are a self-equilibrated system of forces, and as such, their influence diminishes with distance from the interface. For very thick coatings, the top layers would tend to deform in the manner of an unbonded coating. Regarding the relative influence of these two factors, local reinforcement and coating thickness, the evidence of Fig. 19 appears to indicate some predominance of reinforcement. Reinforcement would produce the greatest reduction of interface strain at the section of symmetry, as observed herein, whereas thickness effects would predict maximum influence at the section exhibiting maximum strain. The evidence is weak, however, since the over-all departure is small, and variations within that range may arise from experimental inaccuracies.

Experimental analysis was also undertaken to exaggerate the influence of coating thickness and

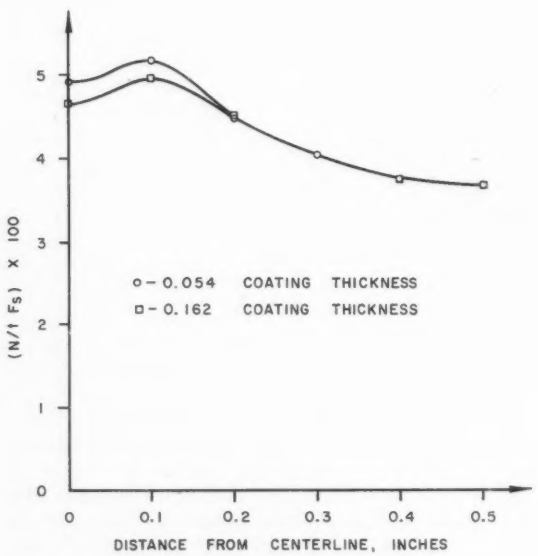

Fig. 19—Effect of coating thickness on birefringence for tensile specimen with transverse hole

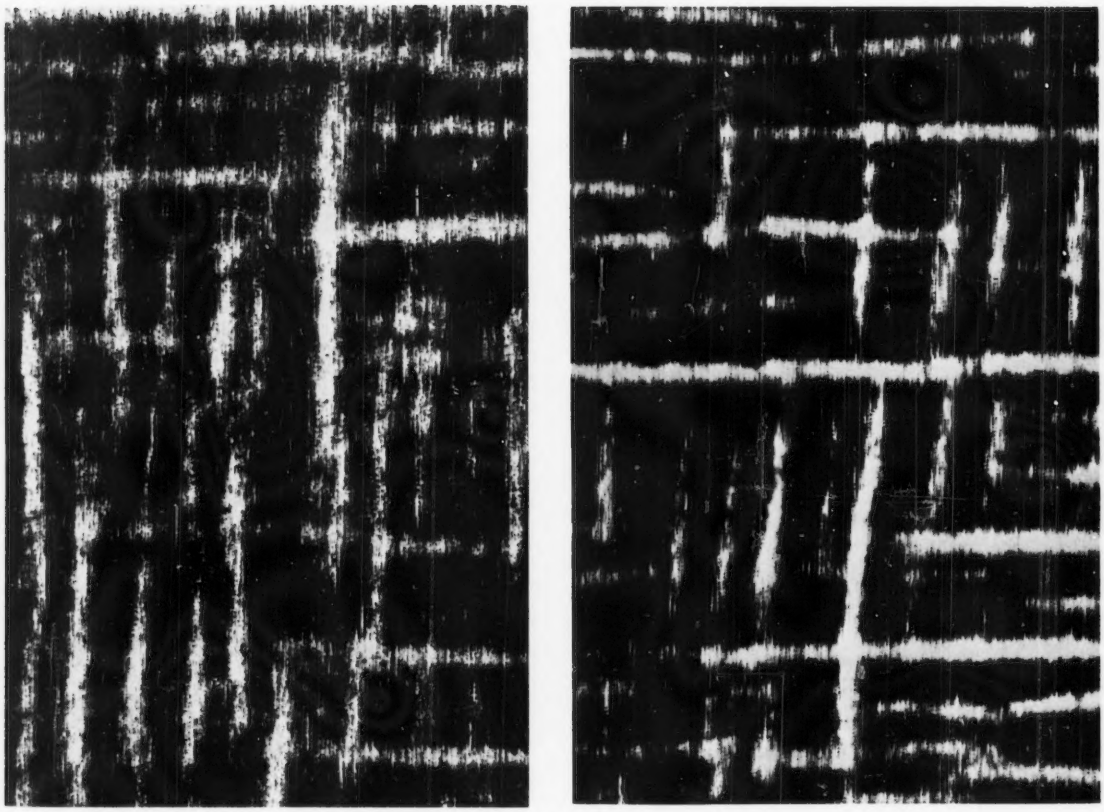

Fig. 20—Birefringence patterns for plastic deformation of mild steel at two typical regions in specimen. Coating thickness: left, 0.122 in.; right, 0.041 in.

strain gradients. This was the analysis of discontinuous plastic deformation. The specimen was a bar of hot-rolled mild steel, $1^1/_2$ x $^1/_4$ x 12 in., with Photostress Type S plastic of $^1/_8$-in. thickness bonded to one face. Plastic deformation was produced in the bar by twisting it about its longitudinal axis until moderate permanent deformation was achieved. Lueder's lines were clearly visible in the metal; these are slip bands, or bands in which the metal experiences very large permanent shear strains. Birefringence patterns are shown in Fig. 20 for two typical regions of the specimen.

Birefringence measurements were taken along line $x - x'$ (Fig. 21) by means of a microscope-type reflection polariscope fitted with a Babinet compensator. The thickness of the coating was reduced in successive operations to obtain the data shown in Fig. 21. Observe that the fringe order in regions between the slip bands diminishes in proportion to coating thickness, whereas the birefringence spikes are not as greatly influenced by coating thickness. Fringe order is not proportional to coating thickness for these local disturbances. Instead, there appears to be an upper limit to coating thickness, beyond which the undulation amplitude ceases to increase. Accordingly, this example represents a qualitative confirmation of coating behavior described by Duffy.[5] While birefringence observations for the case of slip bands provide valuable insight into coating behavior, this is a problem of metallurgy rather than stress analysis. The strain gradients produced in this case cannot develop in homogeneous deformation of continuous bodies.

The last example emphasizes the role of local shear tractions in transmitting strains to the coating. It is now clearly understood that no significant inaccuracies arise in cases where shear tractions are 0. It is equally important to realize that coatings of arbitrary thickness are not applicable to cases in which shear tractions are required in order to maintain continuity between the structure and coating. For maximum accuracy, coating thickness should be small compared to the span over which shear tractions are developed.

Conclusions

1. For the case of plane-stress problems and equal Poisson's ratio of structure and coating, the influence of coating thickness on birefringence developed along free boundaries is almost identically 0.

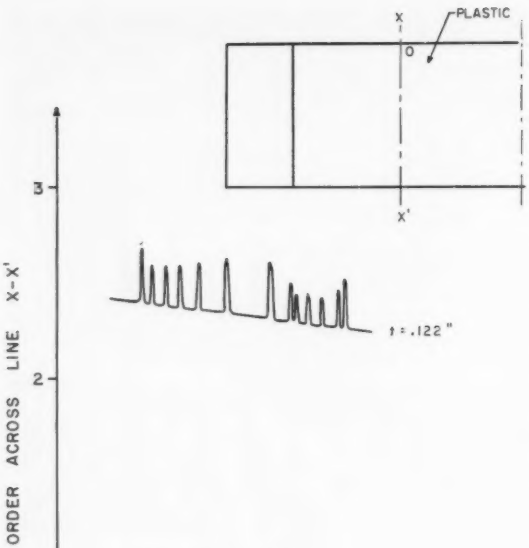

Fig. 21—Birefringence measurements across slip lines

2. For unequal Poisson's ratios and singly connected structures in plane stress, birefringence developed along free boundaries is almost exactly independent of coating thickness; however, situations might arise in cases of complex geometry in which the shear tractions developed as a result of unequal Poisson contractions affect the state of stress and strain in the structure.

3. For singly connected structures in plane stress, very thick coatings behave essentially as independent bodies subjected to prescribed end displacements, i.e., as photoelastic models. In this case, birefringence is independent of Poisson's ratio.

4. In a three-dimensional problem in which coating deformation was controlled by shear tractions developed at the coating interface, strains predicted by a thin coating were 5% greater than strains predicted by a thick coating. The difference is attributed to local reinforcement of the structure by the coating.

5. In the case of extremely high shear strains and strain gradients in plastically deformed mild steel, departures from linearity between birefringence and coating thickness qualitatively confirm the effects studied by Duffy. Extremely thin coatings can be used for such studies.

6. In order to minimize effects of dissimilar Poisson's ratios and local reinforcement, thin coatings are preferable. For most engineering problems, $^1/_8$-in. coatings should be adequately thin. Plane-stress distributions for singly and multiply connected bodies and general surface-strain problems can be analyzed effectively by the method of birefringent-coating measurements.

Acknowledgments

The authors wish to express their appreciation to S. Redner for his valuable theoretical and experimental contributions, particularly for his suggestion to compare bonded and unbonded coatings, and to M. Thayer for his very generous assistance with experimental work and subsequent analysis.

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FUTURE SESA PROCEEDINGS

Each month the central section of EXPERIMENTAL MECHANICS *will be devoted entirely to technical articles. Twice a year these sections will be separately bound and published as the Proceedings of SESA. In this way, all those interested will be able to continue adding these valuable papers to their technical libraries.*

sesa news

1960 Annual Meeting in Berkeley Features Varied Program

EDWARD TELLER IS PRINCIPAL SPEAKER AT BANQUET

In the Berkeley hills overlooking San Francisco Bay and the Golden Gate, some 200 members and guests gathered for the 1960 Annual Meeting of SESA held on October 19–21 at the Hotel Claremont. Featured among the many events of interest in a varied program was the address by Edward Teller, noted atomic physicist from the University of California. His speech sounded the keynote of emphasis for the theme of the three-day meeting: experimental mechanics in the nuclear age.

The main events included the presentation of 17 papers in four technical sessions and the manufacturers' exhibits of experimental equipment, much of which was presented through "live" demonstrations. Other activities covered the Educational Lecture series of three papers on thermal stress, the presentation of the Murray Lecture by R. E. Peterson, the plant tour of the Ames Aeronautical Laboratory, an entertaining ladies' program and various committee and business meetings. The newly elected officers for SESA's 1960–61 term also were installed in Berkeley. They are reported upon elsewhere in this issue.

Dr. Teller on Fission and Fusion

Dr. Teller has been an advocate of the sensible use of power from nuclear reactors, having cited the dangers of mobile power units. In his banquet address he emphasized the relative safety of nuclear reactors—properly designed and operated. He reviewed the peaceful applications of nuclear fission and then went on to describe laboratory-controlled fusion experiments. Emphasis was placed on the desirability of obtaining electrical energy directly from contained "plasma" exciting its magnetic "bottle." He closed by asking when we would be able to obtain Nikita Kruschev's permission to use atomic explosions for such practical application as making new harbors, pulverizing rock for mining and storing thermal energy in the ground.

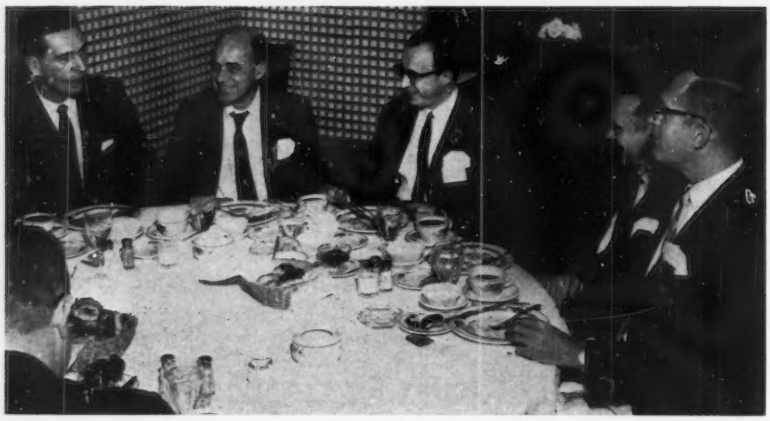
In addition to being professor, physics-at-large, at the University of California, Dr. Teller is associate director of the Lawrence Radiation Laboratory.

Technical Sessions at High Level

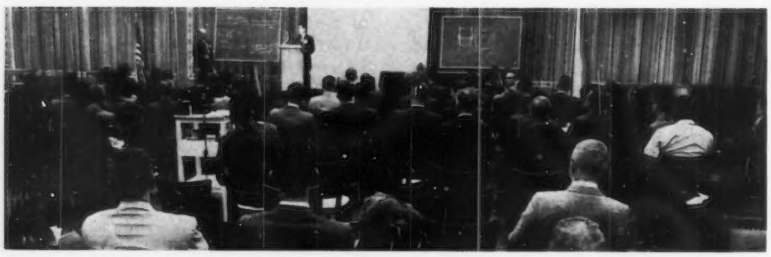
The papers presented at the various technical sessions were well received and generally regarded as up to their usual high standards. New problems, instrumentation and original analyses were in evidence throughout the sessions. In keeping with the spirit of the meeting were papers on stresses in bonded rocket propellant grains, by I. M. Daniels and A. J. Durelli; on stresses in a nuclear reactor head, by G. W. Brewer and J. D. Ingham; on weldable high-temperature gages—preheated for stability, by F. R. Beyer; and on elevated temperature cycling of metals, by R. A. Willem

Registration gets under way. C. R. Smith (foreground) signs in accompanied by W. F. Kirkwood. Behind desk are (left to right): C. E. Makerov and R. L. Morton

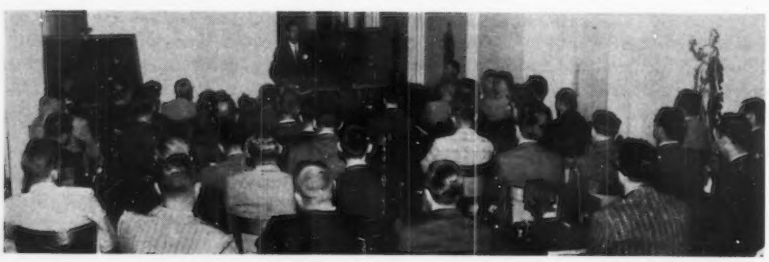
A few of the "chiefs" greet SESA's recently appointed executive secretary. Left to right: Bonney Rossi, Treasurer Bill Murray, Annual Meeting General Chairman Bob Steidel, and Vice-president Irwin Vigness



Author's breakfast on Friday morning. Left to right: G. W. Brown (back to camera), G. E. Bowie, A. J. Durelli, Peter K. Stein, Treasurer Murray and R. W. Clough



A. J. Durelli (with pointer) and E. E. Day (at podium) hold forth at the first technical session



J. L. Meriam giving the first thermal-stress lecture, "Introduction to Thermal Stress, Elastic Calculations and Thermal Stresses in Ships"

Members enjoy a few moments' relaxation during coffee break between technical presentations

and J. D. Morrow. Basic research was characterized by a paper on the effect of dynamic preloads on the mechanical properties of steel, by R. C. Smith and a paper on damping at the contacts of a sphere, by G. E. Bowie and L. E. Goodman. T. Slot described a very useful reflection polariscope for use with photoelastic coatings which gave no evidence of highlight reflections. A thorough instrumentation job for high-frequency vibrational stress and pressure was described by P. K. Stein. A new look at the photoelastic coating gage enabling the separation of the principal stresses was presented by Mr. Stein for the author, F. Zandman.

Many other papers were also worthy of note.

Plant Tour Arouses Interest

All of those attending the Ames Aeronautical Laboratory tour praised these facilities for their uniqueness and the thoroughness with which the testing is done. Both the hypervelocity ballistic facility and the hypervelocity wind tunnel are keeping well ahead of current demands for speed, pressure and temperature in the missile and satellite fields. The five-degree-of-freedom manned space vehicle simulator can very nearly duplicate the motions anticipated and thereby can test pilot reactions under realistic conditions.

Peterson Presents Murray Lecture

Manager of the mechanics department in the Westinghouse Research Laboratories, R. E. Peterson has been known as an outstanding engineer in research and in education. His qualities and his professional record are reflected elsewhere in this issue, under a report of his winning the 1960 Machine Design medal of ASME. As the 1960 William M. Murray Lecturer, Mr. Peterson spoke on "The I dle of Stress Distribution in Fatigue." The lecture was ably presented and well received.

Ladies Enjoy Lively Program

Thanks to the efforts of committeewomen Mrs. T. B. Lane, Mrs. R. F. Steidel, Mrs. R. L. Morton and the cooperation of the guests, the ladies had an enjoyable time. Activities were divided among shopping tours, visiting the San Francisco area by day and by night, luncheon at various places of interest, the Wednesday night banquet and social hours.

Educational Lectures Cover Thermal Stress

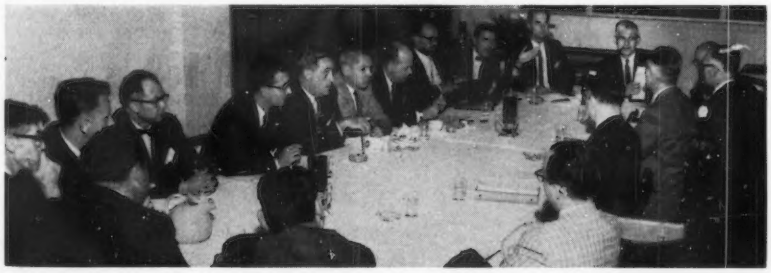
Much interest was shown in the lectures on thermal stress. Professor J. L. Meriam reviewed the field and set up the elastic equations. Then

Committee meeting of local sections chairmen, with Clarence Smith presiding

Dr. Teller, noted atomic physicist, addressing the meeting on "The Future of Nuclear Energy"

The banquet ritual. Left to right, at head table: Secretary Rossi, Vice-president Walter Soroka, Mrs. Soroka, California Section Chairman K. S. Pister, Guest Speaker Edward Teller, Treasurer Murray, Past-president Ed Wenk, and Vice-president Vigness

R. E. Peterson delivering the W. M. Murray Lecture, "The Role of Stress Distribution in Fatigue'



Shown at Executive Committee meeting are, clockwise, starting at gap in foreground: Past-president Milt Leven, Chuck Taylor, Dan Wright, G. F. Weissmann, Cliff Barton, John New, Bruce Sutton, Lou Moffett, Stu Sennet, Clarence Smith, Fred Baley, Ferdi Stern, Past-president Wenk, Secretary Rossi, Vice-president Soroka, Vice-president Vigness, Treasurer Murray and Pete Stein

he proceeded to show how an elementary strength-of-materials approach could be used to predict the stresses in a section of a floating ship's hull subjected to solar heating. K. R. Merckx showed how plastic strains could sometimes reduce stress but, after several cycles, the racheting effect, or strain accumulation, could cause failure. B. E. Gatewood took the example of two integral elements of a beam which are kept at different temperatures and showed how strain accumulation was affected by the strain level at each cycle of loading.

Sponsor Exhibits

A total of sixteen organizations sponsored exhibits at the Claremont Hotel. Listed in alphabetical order, they were as follows: Aerojet-General Corp., Sacramento, Calif.; Allegany Instrument Co., Palo Alto, Calif.; Baldwin-Lima-Hamilton Corp., Waltham, Mass.; B & F Instruments, Inc., Philadelphia, Pa.; University of California—Mechanics and Design; Budd Co., Instrument Division, Phoenixville, Pa.; Electronics, Melbourne, Fla.; Encyclopedia Britannica, San Francisco, Calif.; Gilmore Industries, Inc., Pasadena, Calif.; The Korfund Co., Inc., Westbury, N. Y.; Lawrence Radiation Lab., Livermore, Calif.; Magnaflux Corp., Chicago, Ill.; Ormond Instrumentation Center, Santa Fe Springs, Calif.; Research Inc., Minneapolis 24, Minn.; John Wiley & Sons, Inc., New York, N. Y.; and B. J. Wolfe Enterprises, Northridge, Calif.

To Northern California Section: Plaudits

For the overall success of the 1960 Annual Meeting, for the many hours of preparation and for the numerous details handled during the three-day event, credit goes to the members of the Northern California Section, who were the hosts. Section Chairman K. S. Pister placed the following committee in charge of the affair: R. F. Steidel, general chairman; R. L. Morton, registration and arrangements; G. W. Brown, technical sessions; I. Finnie and M. Godet, educational lectures; A. O. Hardrath, membership; D. M. Cunningham, publicity; D. Pirtz, exhibits; T. B. Lane, plant tours; R. W. Clough, banquet; the Mmes. T. B. Lane, R. F. Steidel and R. L. Morton, women's program.

National Officers Elected for 1960–61 Term

The election of the national officers to serve SESA during the 1960–61 term was announced at the 1960 Annual Meeting held in Berkeley, Calif., on October 19–21. The names and short biographical summaries of the successful candidates are presented to bring current some information concerning them and their backgrounds.

Elected to lead SESA for the coming year, beginning with the close of the Annual Meeting, is President Daniel C. Drucker of Brown University. Dr. Drucker has previously filled a two-year term as vice-president.

In the capacity of vice-presidents are Irwin Vigness of the Naval Research Laboratory and Walter W. Soroka of the University of California. Dr. Vigness is completing the second year of this two-year elective post, while Dr. Soroka moves up from member of the Executive Committee.

The newly created office of treasurer is filled by William M. Murray of the Massachusetts Institute of Technology. Dr. Murray's distinguished record of service to SESA includes the handling of all administrative details since the founding of the Society. He has relinquished these duties with the advent of a full-time, paid executive secretary now required by SESA's expanding activities.

The other members comprising the Executive Committee are as follows: Fred C. Bailey of Lessells and Associates, Boston, Mass.; Benjamin J. Lazan, University of Minnesota; John C. New, National Aeronautical and Space Administration; Charles E. Taylor, University of Illinois; and Edward Wenk, Jr., the Library of Congress. Dr. Lazan and Dr. Wenk are the two most recent living past presidents and, as such, are ex-officio members of the committee.

Of the officers and their careers to date, the following sketches are necessarily brief.

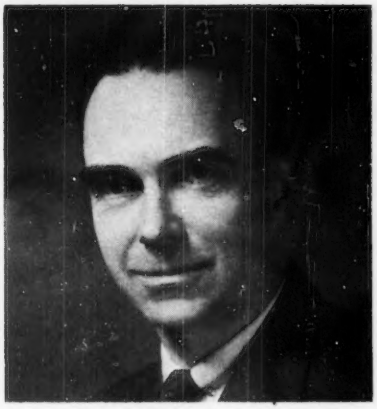
DANIEL C. DRUCKER

Daniel C. Drucker

Born in New York City, Daniel C. Drucker attended Columbia University where, by 1940, he had earned the degrees of B.S., C.E. and Ph.D. in engineering. Three years at Cornell as instructor in mechanics were followed by a term as supervisor at Armour Research Foundation of the Illinois Institute of Technology where, from 1946 to 1947, he was assistant professor of mechanics. Starting at Brown University in 1947 as associate professor in engineering, he became professor

IRWIN VIGNESS

WALTER W. SOROKA



WILLIAM M. MURRAY

in 1950. In 1953 he was made chairman of the Division of Engineering.

Among his affiliations, Dr. Drucker has been active with the ASME as technical editor of the *Journal of Applied Mechanics;* member of the Executive Committee, Applied Mechanics Division; member of special committee on brittle fracture; sponsor in plasticity and experimental stress analysis; and member of the Executive Committee of the Providence Section. Parallel activities with the Engineering Mechanics Division of ASCE included: member, Advisory Board; chairman of Committee on Plasticity; secretary of the Division; president of the Providence Section; president of the New England Council. He has served in various official capacities for the ASEE and on the advisory councils for the Picatinny and Detroit Arsenals. He has also served on several committees of the National Research Council and is a Fellow of the American Academy of Arts and Sciences.

Other memberships include: IAS (associate fellow), AAAS, Society of Rheology, Rhode Island Society of Professional Engineers, Providence Engineering Society, Tau Beta Pi, Sigma Xi. In 1958, he was secretary of the 3rd U. S. National Congress of Applied Mechanics.

Irwin Vigness

A very brief outline of the activities of Irwin Vigness includes several salient features. He undertook undergraduate and graduate studies at the University of Minnesota leading to a Master's degree from the Department of Electrical Engineering in 1931, and a Ph.D. from the Department of Physics in 1934. He remained at Minnesota as an instructor until 1939, when he entered the employ of the U. S. Naval Research Laboratory, Washington, D. C. At present he is head of the Shock and Vibration Branch.

Dr. Vigness has made a number of contributions published in the *Proceedings* of SESA. These have dealt mainly with shock, dynamic loading, vibrations and strain-gage characteristics. He is serving his second year as a vice-president of SESA.

Walter W. Soroka

Graduating from Massachusetts Institute of Technology in 1930 with a degree in mechanical engineering, Walter W. Soroka continued there for graduate study. He earned his M.S. in 1933 and a Sc.D. in 1945, both in the same field, while teaching thermodynamics and fluid mechanics. From 1937 to 1941 he served as a research and development engineer on Servel gas refrigeration units. Working with Chance Vought from 1941 to 1945, he conducted flutter, vibration and landing-impact analyses and tests on fighter aircraft. Following this, he became supervisor of their dynamic analysis group.

Dr. Soroka returned to teaching and academic administrative duties in 1947, when he joined the University of California in Berkeley. Initially in charge of the experimental stress analysis laboratory, he became head of the analog laboratory and then of the acoustics laboratory, his present position. Other duties in the Department of Mechanical Engineering include chairman of the Division of Engineering Design, 1955–59.

He is active as a consultant in architectural and industrial acoustics problems.

William M. Murray

Perhaps the best description of William M. Murray's contributions to SESA comes from the pen of a fellow-member:

"Bill Murray's merits in regard to SESA are so numerous and all-important in the early history of the Society that he well deserves to be called its father. It was his foresight that initiated the transition from the Eastern Photoelasticity Conference to the Society of Experimental Stress Analysis in 1943 and, then, it was his unrelenting effort that made this transition possible. He put his full, great energy behind the formation of the Society, served as its first president and, each year since, has acted as secretary-treasurer. He handled the organization, the membership drive and the publication of the *Proceedings.*

"The founding of the Society years ago came at a critical time in the history of our country. The information disseminated by the Society was of immense value to many engineers engaged in the war effort. Bill Murray continued all through these years—and later, as the membership grew. We are all grateful to Bill for the tremendous amount of work he has done for the Society."

As to his career, Dr. Murray attended McGill University, receiving his B.Eng. in 1932. He later studied at Massachusetts Institute of Technology where he earned his master's degree in 1933 and a doctorate in 1936, both in mechanical engineering. Remaining at MIT, he successively filled the posts of instructor, assistant professor, associate professor and professor. He has held the latter position since 1954. In addition, he has presented and directed undergraduate, graduate and summer courses covering various aspects of experimental stress analysis at MIT, Lowell Institute, Northeastern University, University of California and the Southwest Research Institute.

Dr. Murray is a registered professional engineer in the Province of Quebec and in the State of Massachusetts. He has acted as consultant in the field of experimental stress analysis for a number of industrial organizations. His affiliations include the

FRED C. BAILEY

BENJAMIN J. LAZAN

JOHN C. NEW

following professional societies besides SESA: Engineering Institute of Canada, ASEE, ASTM and ASME. His ASME activities include member of Executive Committee, secretary, chairman—all in the Applied Mechanics Division.

Among the many honors awarded him are: the establishment of the William M. Murray Lectureship by SESA, election as a Fellow of the American Academy of Arts and Sciences and the British Association Medal for undergraduate proficiency in mechanical engineering while at McGill. He is a member of Psi Upsilon college fraternity and of the honorary societies of Sigma Xi, Tau Beta Pi, Pi Tau Sigma, as well as the Newcomer Society of North America. Dr. Murray is the author and co-author of over 27 books, articles, bulletins and monographs on a number of subjects dealing with experimental stress analysis and other fields of engineering research and development.

Fred C. Bailey

After attending the local schools in his native town of Claremont, N. H., Fred C. Bailey saw active duty with the U. S. Navy from 1944 to 1946. He then entered Massachusetts Institute of Technology, majoring in metallurgy and mechanics. After earning an S.B. in general engineering in 1948, he remained at MIT for graduate work and, in 1949, received his S.M. in mechanical engineering.

Joining the Caterpillar Tractor Co., Mr. Bailey became a research engineer in the Fatigue and Stress Analysis Section where, from 1949 to 1952, he made vibration and stress-analysis studies of diesel engine and earth-moving equipment components. With the National Research Council from 1952 to 1955, he successively held the posts of technical secretary, assistant technical director and acting technical director of the Committee on Ship Steel and Ship Structural Design. He was concerned here with the administration of research on brittle fracture, welded-steel structures, ship structural components and stress analysis of ship structures. Since 1955, he has been associated with Lessells and Associates, Inc., Boston, Mass., first as project engineer, then as senior project engineer and lately as executive vice-president. His work now includes theoretical and experimental stress analysis, machine design, materials selecting and testing and applied mechanics.

A past chairman of the New England Section of SESA, Mr. Bailey is also a member of ASME, AWS and is a registered professional engineer in Massachusetts.

Benjamin J. Lazan

A native of New York, Benjamin J. Lazan completed his secondary schooling in Freehold, N. J. Graduating from Rutgers in 1938 with a B.S. in mechanical engineering, he entered Harvard University where he earned an M.S. degree in applied mechanics. Entering Pennsylvania State College in 1939 as an instructor in the Department of Engineering Mechanics, he earned his Ph.D. in 1942 and was appointed assistant professor of engineering mechanics; during this time he was in charge of research projects in dynamic testing of materials.

Joining the Sonntag Scientific Corp., a Baldwin Lima-Hamilton Corp. affiliate, in 1942, Dr. Lazan became project engineer, chief engineer and, in 1944, executive vice-president. Responsible for the development of several machines now used in static and dynamic testing, he was also in charge of a government research project on a jet-propulsion engine.

In 1946 Dr. Lazan became associate professor and director of the Materials Laboratories at Syracuse University. In 1948 he was promoted to professor and head of the Department of Materials Engineering. At Syracuse he directed research projects for the Office of Naval Research, the U. S. Air Forces and private industry.

Upon joining the University of Minnesota in 1951, he was appointed professor of materials engineering. Later, he became director of the Engineering Experiment Station, head of the Department of Mechanics and Materials, associate dean of the Institute of Technology and, most recently, professor and head of the Department of Aeronautical Engineering.

During the past several years, Dr. Lazan has been retained as consultant by a number of companies.

Author of about 50 papers dealing with research in the mechanical properties of materials under dynamic forces, Dr. Lazan has received the following outstanding awards: the A. Noble Prize from ASME (1943); the Charles Dudley Medal from ASTM (1949); the Henry Howe Medal from ASM (1951); and the Murray Lectureship from SESA. He is a member of Tau Beta Pi, Phi Beta Kappa, Sigma Xi and ASEE, in addition to the above-mentioned and other societies. Dr. Lazan is immediate past president of SESA.

John C. New

A native of Warrensburg, Mo., John C. New graduated from the University of Missouri in 1943 with a B.S. in civil engineering. After serving as an instructor in engineering mechanics at the same school, he joined the Naval Ordnance Laboratory in Washington, D. C., in 1944. During the next 15 years with that organization, he was active in establishing a new research and de-

velopment laboratory at White Oak, Md., developing new methods and facilities for evaluating naval ordnance and advanced weapons systems, including nuclear depth bombs and the Polaris system.

He earned his M.S. in mechanical engineering from the University of Maryland in 1950. The Navy awarded him the Meritorious Civilian Service Award.

Mr. New joined the NASA family in 1959 where, at the Goddard Space Flight Center, Greenbelt, Md., he heads the Test and Evaluation Division which is responsible for all testing of spacecraft systems prior to their actual launching.

Active in professional societies, he holds membership and various offices in the Institute of Environmental Sciences, Research Society of America, SESA and ASCE. He has been active in SESA since its founding and has served as president of the Washington Area Section. Currently chairman of the national Publicity Committee, he has served on the Papers and Proceedings Committee. He has authored numerous papers and holds several patents. The first elected chairman of the DOD Interservice Group on Shock, Vibration and Associated Environments, he has served on several other national committees.

Charles E. Taylor

Charles E. Taylor hails from West Lafayette, Ind. He attended Purdue University where he received a B.S. degree in mechanical engineering in 1946 and an M.S. degree in engineering mechanics in 1948. Continuing his graduate studies at the University of Illinois he earned his Ph.D. in theoretical and applied mechanics in 1953. During World War II, Dr. Taylor served in the Pacific Theater as an infantry officer.

His professional experience includes two years of teaching and research at Purdue University, ten years at the University of Illinois and two and one-half years as a structural research engineer at the David Taylor Model Basin in Washington, D. C. Since 1957, he has been professor of theoretical and applied mechanics at the University of Illinois. Dr. Taylor is the author of nine technical articles and is a member of SESA, ASME, ASEE, Pi Tau Sigma and Sigma Xi. He is serving as a member of the SESA Executive Committee and has been chairman of the Papers and Proceedings Committee.

Edward Wenk, Jr.

Edward Wenk, Jr., spent his undergraduate days at the Johns Hopkins University, where, in 1940, he earned a B.E. degree. He later undertook graduate studies, leading to an M.S. degree from Harvard University in 1947, and to a Doctor of Engineering degree from Johns Hopkins in 1950.

From 1941 to 1942, Dr. Wenk was employed by the Boston Naval Shipyard doing work in naval architecture. He then became associated with the David Taylor Model Basin, first as naval research scientist from 1942 to 1950, and then as chief of the Structures Division, from 1950 to 1956. In 1956, he accepted the position of chairman of the Department of Engineering Mechanics at Southwest Research Institute. In 1959 he became senior specialist, science and technology, of the Legislative Reference Service, Library of Congress.

Dr. Wenk has held several honorary positions. A driving force behind the present realignment of the SESA's activities, he was national president during 1957–58 and chairman of the Papers and Proceedings Committee for the 1953–54 fiscal year. He is presently chairman of the Journal Advisory Committee and a member of the Executive Committee.

Other society affiliations include the ASCE, ASME, Pressure Vessel Research Committee of the WRC and panel chairman for the Committee on Undersea Warfare, National Academy of Sciences.

His awards include Sigma Xi, Tau Beta Pi and the Navy Civilian Meritorious Award.

Dr. Wenk is a registered professional engineer. He has contributed 50 or so papers in the fields of applied mechanics, experimental stress analysis, ship and submarine design, structural analysis of deep-diving submarines and in government science policy.

SESA Receives NSF Grant

A grant of $45,000 to extend over a three-year period has been awarded by the National Science Foundation to the Society for Experimental Stress Analysis for the purpose of partial support in establishing a new journal, EXPERIMENTAL MECHANICS. The grant, which became effective Oct. 4, 1960, allocates $20,000 for each of the first two years of operation and $5000 for the third year, by which time the *Journal* will be expected to become self-supporting.

CHARLES E. TAYLOR

EDWARD WENK, JR.

SESA Proceedings

Each month the central section of EXPERIMENTAL MECHANICS will be devoted entirely to technical articles. Twice a year these sections will be separately bound and published as the *Proceedings*. In this way, all those interested will be able to continue adding these valuable papers to their technical libraries.

Plans Released for 1961 Spring Meeting in Philadelphia

While final arrangements are still in process for the 1961 Spring Meeting of SESA, several items of interest give every indication of a highly attractive program. This year, the meeting will be held at the Benjamin Franklin Hotel in Philadelphia, Pa., on May 10–12, with the Delaware Valley Section acting as hosts.

The technical presentations will consist of about 20 or more papers dealing with a number of new approaches to various instrumental methods of analysis and measurements. Some of these include studies of transient accelerations, calibration methods, effects of lead-wire resistance, evaluation of gas-turbine blades, elastic stability and fatigue testing—to mention a few. One group of papers will carry the theme of the meeting: "Experimental Mechanics at High Temperatures." Of the five sessions planned, two are scheduled for Wednesday, May 10; one for Thursday morning, May 11; and two for Friday, May 12.

Tentative arrangements are being made for a plant tour on Thursday afternoon, preferably to the Eddystone Power Plant. This event should be of great interest to many attending the meeting.

A banquet has been scheduled for Thursday evening, with Frank Tatnall acting as toastmaster. In addition, plans are being made for an outstanding speaker to address the group on a timely subject.

The ladies, as usual, are getting a great deal of attention. A full program of activity is being scheduled for them. The members are, therefore, asked to keep their ladies fully informed.

Other plans still in the tentative stage include the possibility of a seminar on Wednesday evening, dealing with the role of computers in experimental mechanics. As a result of this activity, it is possible that a second plant tour may be arranged.

More definite details on what promises to be a highly eventful Spring meeting will appear in future issues of EXPERIMENTAL MECHANICS.

SESA to Sponsor First International Congress

The first International Congress on Experimental Mechanics ever to be held has been scheduled for Nov. 1–3, 1961, at the Hotel New Yorker in New York City.

Groundwork for this outstanding event has been proceeding quietly. Although still some months distant, the Congress has already received the favorable attention of leading European scientists. Both firm and tentative commitments have been received from representatives of France, Netherlands, Sweden, and the United Kingdom, while excellent possibilities now exist for representation from Germany, Italy, Portugal and Spain.

SESA's 1961 Annual Meeting is thus expected to carry wide international significance. In addition, the scope of the technical sessions in the broad field of experimental mechanics offers numerous inviting possibilities. Many new ideas and valuable contributions are expected.

At the same time, an exposition of instruments and equipment will be on view. Manufacturers will have an unequaled opportunity to display the latest products and to demonstrate their methods before an exceptional audience.

BOUND VOLUMES OF

PROCEEDINGS AVAILABLE

Still available are a number of bound volumes of the series **Proceedings of the Society for Experimental Stress Analysis.** Published twice yearly, these volumes comprise the technical papers presented at national meetings and contain the results and descriptions of analytical and experimental investigations, as well as discussions of technique and instrumentation studies.

Price per copy: $7.00 to nonmembers and $6.00 to members; plus postage. Copies may be ordered through the Society for Experimental Stress Analysis, 21 Bridge Square, Westport, Connecticut.

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section reports

Chicago

Creep in Refinery Operations

The October meeting of the Section was held at Phil Schmidt's in Hammond, Ind. Preceding the meeting, the Standard Oil Co. (Indiana) conducted a guided tour of their research and refinery facilities in Whiting, Ind. Of special interest to members was the creep laboratory.

After dinner, the business meeting was held. Chairman LeRoy A. Grotto related that the participation of industry educational institutions and individuals working in the field of experimental mechanics is not as great as it should be for an area as large as metropolitan Chicago. Mr. Grotto emphasized that every effort should be made to build the Chicago Section of the SESA from the standpoint of membership and greater cooperation, and to try to arrange for an annual national meeting of the SESA to be held in Chicago.

New business included the election of Warren Klinke of the Electro-Motive Division, GMC, to the office of secretary-treasurer, replacing Ed Rapciak who passed away suddenly.

Immediately following the business meeting, Dr. Randall of the Standard Oil Co., who is the director of creep-testing research, presented a lecture which explained some of the problems concerning creep in refinery operations. Dr. Randall, who received his Ph.D. from the University of Illinois in 1948, also reviewed the results of his research over the past few years and detailed his techniques in obtaining these results. By a very unique feedback and balance system, Dr. Randall was able to control the test temperature $\pm 1/6°$ F for a period of one week throughout the elevated test-temperature range. This is of particular significance, since small variations in test temperature produce large variations in creep rate. Dr. Randall performed both constant-load and constant-stress creep tests. Constant stress was achieved by a bell-crank lever arm, the lever ratio of which varied as the elongation of the specimen. Good accuracy is obtained up to 40% of the life of the specimen.

After the lecture, an informal discussion took place, with Dr. Randall answering questions by the members.

(Reported by J. C. Tamburino for the Chicago Section)

Hudson-Mohawk

Dynamic Stress-Concentration Factors

R. E. Weigle, chairman, presided over the first meeting of the Hudson-Mohawk Section of the SESA at the Watervliet Arsenal on Oct. 11, 1960. Attendance was approximately 40.

R. Guernsey of the Advisory Board introduced the speaker, J. Dally of Cornell University, who spoke on "Dynamic Stress-concentration Factors."

In his presentation, Dr. Dally described experiments in dynamic photoelasticity currently in progress at Cornell University. Photoelastic flat tensile specimens with circular holes were impacted on one end with falling weights. With high-speed photography, the advances of the stress waves were followed and stress-concentration factors for the hole were found as a function of ratio of hole diameter to specimen width. In general, the stress-concentration factor was found to be smaller than in the corresponding static situation.

(Reported by J. P. Partell for the Hudson-Mohawk Section)

SESA Section Meeting Calendar

January 12

MILWAUKEE Chapter. Engineers Society Building, 3112 West Highland Boulevard, Milwaukee, Wisc. "Effects of Vibration on Man," by Richard J. Hornick, chief research psychologist, Bostrom Corp.

January 17

PITTSBURGH Section. 8:00 PM. Westinghouse Research Laboratory, Pittsburgh, Pa. "Magnetohydrodynamics," by Stewart Way, Westinghouse Research.

January 19

HUDSON-MOHAWK Section. 8:00 PM. Flamingo Restaurant, Kingston, N. Y. "How to Construct or Correct an Analytical Structural Model from Experimental Measurements," by R. M. Mains, General Engineering Lab., General Electric Co.

February 1

NEW ENGLAND Section. Joint meeting with SNT. Dinner: 6:30 PM. Talk: 7:45 PM. Faculty Club, MIT, Cambridge, Mass. "Progress in Experimental Stress Analysis," by Frank Tatnall, The Budd Company.

February 2

HUDSON-MOHAWK Section. Latham, Mass. Talk by F. Wendt, Missile & Space Vehicle Dept., General Electric Co.

February 10

SOUTHWEST Section—Spring Meeting. Admiral Kidd Club, San Diego, Calif. Talk and film on "High-temperature Testing of the X-15 Aircraft," by O. L. Gillette of North American Aviation.

EDITOR'S NOTE: Notices to be published in any one issue must reach SESA headquarters prior to the 15th of the second previous month. Give full information concerning date, time, place, topic and speaker for each meeting.

Northern Ohio

Strain-gage Application

On Oct. 13, 1960, the Northern Ohio Chapter was very fortunate to have again, as the guest speaker, the inimitable Bill Bean of Detroit, Mich. Mr. Bean's knack for common-sense practicality never fails to jar his audiences out of their complacency. The evening's program was preceded by a buffet dinner in an atmosphere of Hawaiian embellishment, enjoyed by 161 members and guests.

Mr. Bean opened the meeting with a particularly difficult problem involving a pressure vessel undergoing rapid and extreme temperature changes. Strain-gage readings, being sensitive to both temperature and strain, must be related to the zero-stress level for the temperature detected at the instant of strain measurement. This necessitates the use of a temperature-sensing device, such as a thermocouple or temperature gage, placed in the immediate vicinity of the strain gage.

Temperature gages are similar to strain gages except for the fact that they are sensitive to temperature changes only.

The zero-stress reference level for a strain gage may be obtained by mounting a gage on a free cantilever. The apparent strain output is read versus the equalized cantilever temperature. A sufficient number of readings are taken to cover the expected test temperatures.

Temperature-compensated strain gages are also available furnished with calibration curves of apparent strain output versus temperature.

Mr. Bean's lectures are never complete without his display of instruments and aids for the installation and reading of strain gages. The opera-glass spectacles appear to be just the thing for positioning these small gages at arms length.

(Reported by Howard F. Calvert for Northern Ohio Chapter)

Southwest

Role of Materials in Experimental Mechanics

The Southwest Section's Fall meeting was held in Los Angeles on Wednesday, Oct. 12, 1960. Although the meeting was scheduled one week prior to the national meeting, 45 members and guests attended, which was gratifying. Following dinner, D. M. Forney, Jr., Materials Laboratory, WADD, spoke on "The Role of Materials in Experimental Mechanics." The first part of Mr. Forney's talk consisted of a comprehensive survey of the state of material development at the present time and the relationship to design demands. This part was followed by a short film on the mechanism of crack propagation. The final part of the talk was a comprehensive discussion on the necessity of design and materials groups working together with actual examples of in-service failures to support the arguments.

The second speaker was J. C. Sanchez of Electro-Optical Systems. He gave a short talk and demonstration on a new piezoresistance strain gage or semiconductor strain gage. These gages are capable of measurements up to 6000 microstrain. In a 4-active bridge at 2000 microstrain, bridge supply voltage 20 V.D.C., 1000 ohm gage, an output of 5.2 v is obtained.

(Reported by E. K. Winslow for the Southwest Section)

Washington Area

Annual Field Trip

It was a fine October 5 morning when, with true early American spirit, a hardy band of 35 members and guests of the Washington Area Section set out to brave the unmapped wilds of Balti-

1960-61 Chairmen and Secretaries of Chartered Local Sections of the SESA

SECTION	CHAIRMAN	SECRETARY
Central Indiana	Prof. Fred J. Bogardus Mechanical Engineering School Purdue University West Lafayette, Ind.	M. G. Hoffman Allison Division General Motors, Plant 8 Indianapolis 6, Ind.
Chicago	L. A. Grotto Applied Mechanics—CEED International Harvester Co. 10400 North Ave. Melrose Park, Ill.	Warren Klinke 107 Forest Avenue Riverside, Illinois
Delaware Valley	Louis B. Moffett, III 110 North Monroe Avenue Wenonah, N.J.	Robert R. Moser 232 E. Queen St. Philadelphia 44, Pa.
Hudson-Mohawk	Dr. R. E. Weigle Watervliet Arsenal Watervliet, N.Y.	T. Slot General Electric Co. Schenectady, N.Y.
Mid-Ohio	Prof. Paul F. Graham Ohio State University Department of Engineering Mechanics 215 N. 19th Ave. Columbus 10, Ohio	Robert J. Eiber Battelle Memorial Institute 505 King Ave. Columbus 1, Ohio
Milwaukee	William H. Bloedorn Chain Belt Corp. P. O. Box 2022 Milwaukee 1, Wis.	Donald E. Niles 17750 Bonnie Lane Brookfield, Wis.
New England	Joseph Blahm Watertown Arsenal Watertown, Mass.	Alan Sapowith Allied Research Assoc. 43 Leon St. Boston 15, Mass.
New York Metropolitan	Prof. Edward R. Lewis Department of Engineering, Hofstra College, Hempstead, L. I., N. Y.	Sigmund Black % Curtiss-Wright, Corp., Aero Division, Woodridge, N. J.
Northern California	Karl Pister Engineering Materials Laboratory University of California Berkeley, Calif.	Prof. D. M. Cunningham 101A Mechanics Bldg. University of California Berkeley, Calif.
Northern Ohio	Howard F. Calvert National Aero & Space Adm. 21000 Brookpart Road Cleveland 35, Ohio	Donald V. Langmeyer Cleveland Pneumatic Tool Co. 3781 East 77 Cleveland 5, Ohio
Ottawa-Montreal	N. K. Norris Department of Mines and Technical Surveys, 601 Booth Street, Ottawa, Ontario	L. W. Gold, Division of Building Research, National Research Council Ottawa, Ontario

more to inspect the facilities of two pioneers of automation. The occasion was the Section's annual field trip, which was capably arranged this year by Ralph Barclay to include a pair of interesting tours.

The first tour, at the Continental Can Co., covered automatic can manufacturing. Starting at 10 A.M. with the lithographing process, the group followed the production line for the can bodies through the slitting, rolling, soldering, proof testing, end flaring and end-crimping processes. On a separate line, it was observed how the ends are punched out and edged with a sealing compound.

Following an enjoyable (if sober) repast, the group wended its way to the Carr-Lowrey Co. for an inspection of their automated glass-bottle production. The guides led the group past the batching and mixing areas and the glass furnaces to the fascinating and near-human robots called bottle-making machines. The tour continued to the annealing furnaces and, finally, to the decorating machines.

The nightshift labor forces were already trudging in before the last weary wanderer, with propaganda leaflets clutched tightly in his hand, turned his headlights toward the Expressway for the ride home. Colorful beer cans and perfume bottles danced merrily in his head as he wondered what program activities Dr. Barclay would dream up next.

(Reported by L. Mordfin for Washington Area Section)

Pittsburgh	I. D. Eaton 126 Madison Drive New Kensington, Pa.	W. R. Midgley U. S. Steel Applied Research Research Lab. Monroeville, Pa.
South Central	Dr. M. M. Lemcoe Southwest Research Institute 8500 Culebra Road San Antonio 6, Tex.	G. L. Thompson 137 Walnut Hill Village Dallas 20, Tex.
Southern Michigan	Robert P. Keller 1837 Earlmont Berkley, Mich.	Melvin A. Walck 30015 Eastfield Farmington, Mich.
Southern Ohio	R. A. Thomson University of Dayton Dayton, Ohio	J. H. Jaspers CTL Division Studebaker-Packard P. O. Box 227 Cincinnati 15, Ohio
Southwest	G. D. Lindeneau 9022 Koonce Drive Spring Valley, Calif.	E. K. Winslow 13418 Powers Road Poway, Calif.
Washington Area	Dr. Myron E. Lunchick Code 725 David Taylor Model Basin Washington 7, D. C.	Leonard Mordfin 3028 Industrial Bldg. National Bureau of Standards Washington 25, D. C.

Representatives in Organizing Areas

Denver	Mike H. Barrett Ketchum, Kunkle & Hastings Consulting Engineers 730 Kalamath Denver, Colo.
Florida	George R. Behel 2611 Lotafun Ave. Winter Park, Fla.
Great Salt Lake Region	Prof. C. S. Barton Department of C. E. Science Brigham Young University Provo, Utah
Kansas City	J. N. Canfield Aviation Gas Turbine Division Westinghouse Electric Corp. P. O. Box 288 Kansas City, Mo.
Minneapolis	Herbert C. Johnson Research, Inc. P. O. Box 6164, Ednia Branch Post Office Minneapolis 24, Minn.
New Mexico	Max McWhirter 3700 Hannett N. E. Albuquerque, N. Mex.
Oklahoma	Prof. James O. Melton, Dept of Theoretical and Applied Mechanics College of Engineering, University of Oklahoma Norman, Oklahoma
Phoenix	P. K. Stein 5602 E. Monte Rosa Phoenix, Ariz.
Seattle	Prof. Emmett E. Day Department of M.E., University of Washington Seattle 5, Wash.
Mexico	Alfred Olivares Teposteco 7-7 Mexico D. F.
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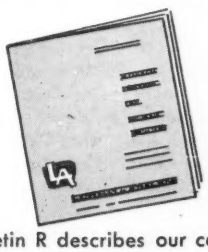

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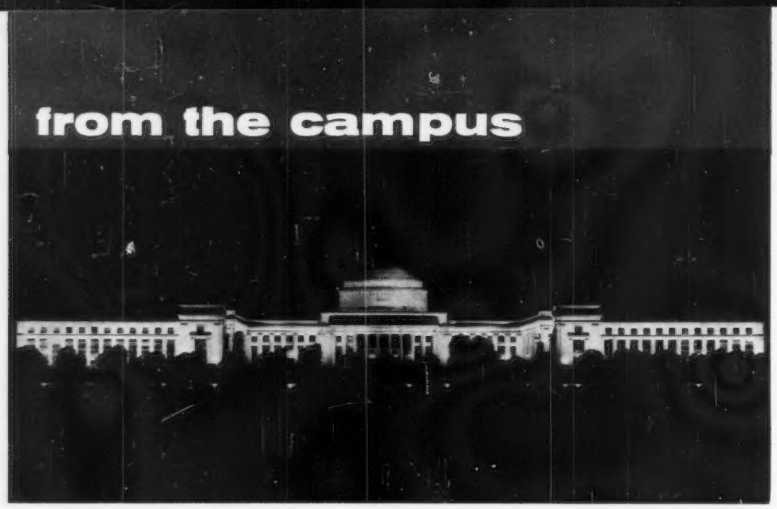

Night View—Massachusetts Institute of Technology

MIT TO OFFER SUMMER COURSES

A one-week course in industrial photoelasticity and two 1-week courses in strain-gage techniques will be offered this summer at the Massachusetts Institute of Technology. The photoelasticity program will be designed to help those in industry to learn the latest developments in the use of polarized light in problems of stress analysis. Emphasis will be on ways in which this technique can help solve industrial problems. No previous knowledge of the subject is required although the academic level is suited to those with a bachelor's or master's degree in engineering, physics or metallurgy.

The strain-gage programs will provide a coordinated presentation of characteristics and uses of wire- and foil-resistance strain gages and allied instrumentation. The topics selected will benefit those who are already skilled in stress analysis but who have little experience in electrical instrumentation; also, they will prove valuable to experts in electronics who are not familiar with various aspects of stress analysis

Further details will be announced at a later date.

BIOMECHANICS RESEARCH CENTER AT WAYNE STATE UNIVERSITY

A Biomechanics Research Center has been established at Wayne State University. This forward step provides a formal organization for an activity that has existed at Wayne for the past twenty years. During this time the Departments of Neurosurgery and Anatomy and the Department of Engineering Mechanics have collaborated on many research problems of joint interest to medicine and engineering.

Professor H. R. Lissner

The operation of the Biomechanics Research Center is the responsibility of a committee consisting of the Deans of the Colleges of Medicine and Engineering. The sponsorship of research has included contributions by governmental agencies, foundations, private industry and research scientists who were intensely interested in the investigations they were pursuing.

The greatest effort has been devoted to studies of the dynamic behavior of the human body and its component parts, and the determination of its tolerance to impact loading. Some of the research in this category has been concerned with the deformation and fracture behavior of the human skull subjected to blows in all regions and at different velocities; the determination of stress and deformation in the pelvis and spine subjected to dynamic loading; the behavior of the long bones under bending and torsional impact loading and a comprehensive study of the mechanism of cerebral concussion.

Other kinds of research have included static testing of spongy and compact bone to determine physical constants, fatigue testing of bone as a material and fatigue testing of complete single bones and the lumbar spine. The latter tests were undertaken in a project to determine the mechanism of intervertebral disk rupture. Other experimental work has involved brain tumor detection methods and studies of blood volume flow in intact arteries. Studies of stresses in the manidible are currently being undertaken, and another project concerns the mechanical measurement of muscle force in the living human. In addition to the foregoing tests, considerable work has been done with the automobile manufacturers in the area of crash safety design, and research in this field is expanding rapidly.

Graduate students in engineering mechanics, having a primary interest in the field of biomechanics, are given an opportunity to participate in research in this area and may elect a thesis subject in biomechanics.

In conjunction with these developments, the graduate program of the WSU Engineering Mechanics Department has been extended to the doctoral level. Graduate students who complete the course and dissertation requirements will become eligible for the Doctor of Philosophy degree. Professor H. R. Lissner, chairman of the Engineering Mechanics Department at Wayne, announces that the following fields of specialization are open to doctoral applicants: mechanics of solids, elasticity, plasticity, strength of materials, vibrations and dynamics, fluid mechanics and biomechanics.

BRIGHAM YOUNG EXPANDS

The campus of Brigham Young University at Provo, Utah, is showing many changes. Several buildings are in the stage of completion, including a new administration building featuring a contemporary design shaped as an X, a new business administration building and a new, completely air-conditioned library of five stories which will house one million volumes.

The five-year engineering program in the fields of civil, mechanical, electrical and chemical, which was begun only eight years ago just this fall, has progressed to the point where now programs for master's degrees have been initiated. In addition, the Engineering Council for Professional Development has stamped its approval on the undergraduate curriculum by issuing accreditation to the engineering programs in civil, mechanical and electrical fields.

The total undergraduate engineering enrollment has grown to approximately 1000 students as compared to 11,000 total University enrollment.

personnel
in the news

CLARKE AND KREBS PROMOTED BY DATEX

Promotion of Kenneth W. Clarke to product manager for heavy industrial systems has been announced by the Datex Corp., Monrovia, Calif.

Mr. Clarke has been with Datex since November 1955 and was the manager of the Datex midwest regional office in Skokie, Ill.

He received his B.S. degree from Brown University. Following more than three years' service in the U. S. Navy during World War II, he was an instrument engineer on a wind-tunnel project and project engineer for another instrument firm.

In his new position, Mr. Clarke will be responsible for developing plans and policies with the objective of expanding the company's product line and markets among users of heavy industrial equipment.

James W. Krebs succeeds Mr. Clarke as manager of the Datex midwest regional office.

Mr. Krebs, who joined Datex as a sales engineer in the midwest office in January 1960, was formerly with Gilmore Industries. He holds a B.S.M.E. degree from Illinois Institute of Technology and did graduate work at Case Institute.

CUMMINS TAKES LEAVE OF ABSENCE

D. J. Cummins, vice president—engineering, will take a leave of absence from Cummins Engine Co., Inc., Columbus, Ind., after 40 years of service. This announcement was made by E. Don Tull, Cummins president, who said Mr. Cummins will continue to serve the company in a consulting capacity.

Mr. Cummins, who has been with the company since its inception in 1919, has held many positions throughout his 40 years with Cummins, including those of laboratory manager, manager—engineering, quality-control manager, managing director—Cummins Engine Co., Ltd., in Shotts, Lanarkshire, Scotland, and vice-president—engineering.

He was one of the company's first field service representatives. During those early years, he traveled the country on application and engineering work. Later, as quality-control manager, Mr. Cummins established the present quality-control systems which the company now uses.

The Cummins Engine Co. is a Corporation Member of the Society for Experimental Stress Analysis.

PETERSON HONORED BY ASME

R. E. Peterson, manager of the mechanics department of the Westinghouse Research Laboratories, was awarded the 1960 Machine Design Medal of the American Society of Mechanical Engineers at its annual meeting held in New York City last November.

Mr. Peterson was cited for his "eminent achievement and distinguished service in the field of mechanical design; for numerous creative contributions and teaching in research, development, application and design of machinery to prevent mechanical failure; and for outstanding accomplishment in the development of young engineers and scientists, both through industrial and university associations."

A 33-year veteran with Westinghouse, Mr. Peterson did his undergraduate and graduate work at the University of Illinois. He presently heads the company's central research program in heat transfer, fluid mechanics, lubrication, vibration, stress analysis and mechanics of materials.

A specialist in mechanics of materials, fatigue of materials and fracture analysis, Mr. Peterson has written some 55 scientific papers and has contributed to seven engineering handbooks on these subjects. He is author of the book *Stress Concentration Design Factors*.

Apart from his contributions to the science of mechanics, and also recognized by the ASME award, are Mr. Peterson's contributions to the development of outstanding young mechanical engineers. In 1956 he established at the Westinghouse Research Laboratories the Advanced Mechanics School. Each year the program provides selected graduate engineers an entire year of theoretical and experimental study that leads to the master's degree at the University of Pittsburgh.

The rank of Fellow has been conferred on Mr. Peterson by ASME. He has served SESA as president and the ASTM as director. In 1954 he received the ASTM Award of Merit.

WILSON NOMINATED ASSOCIATE TECHNICAL DIRECTOR

The Naval Ordnance Laboratory in Silver Spring, Md., announced recently the nomination of Robert E. Wilson as associate technical director for aeroballistics.

Dr. Wilson will be responsible for all phases of NOL's basic and applied research in aerodynamics, fluid mechanics, ballistics and mathematics leading to new concepts in the development of high-speed ballistic missiles and weapons for the modern Navy. Particular effort will be devoted to pioneering ballistic missile re-entry problems.

Dr. Wilson will serve as a member of the Laboratory Directorate and actively participate in the technical and administrative policy-making for the Laboratory.

He replaces Hermann H. Kurzweg who was named assistant director of

R. E. Peterson

Robert E. Wilson

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research at the National Aeronautics and Space Administration.

NAWALINSKI APPOINTED

Thomas E. Nawalinski has been named manager of sales promotion and advertising for Non-Linear Systems, Inc.

Mr. Nawalinski will be responsible for all national advertising, publicity and trade-show arrangements for NLS. He will also direct the company's training courses for customers.

Thomas E. Nawalinski

Mr. Nawalinski joined Non-Linear in 1956 as chief applications engineer, a position he has held until his new appointment. He came to NLS from Convair-Astronautics, San Diego, where he headed the Atlas missile autopilot test equipment group.

Prior to that he was with the Martin Co., Baltimore, Md., for six years as a senior electronic engineer.

Nawalinski received his B.S.E.E. degree from Drexel Institute of Technology, Philadelphia.

HILL AND MOORE NAMED BY ALCOA

The Research Laboratories of the Aluminum Company of America, New Kensington, Pa., have announced that H. N. Hill has been made scientific advisor, equivalent in importance and status to division chief. Formerly the chief of the Engineering Design Division, he will continue to serve as a member of the Research and Development Committee, the Joining Subcommittee, the Task Committee for Automation of Rolling Mills, the Task Committee of Aluminum Armor Materials Improvement and as chairman of the Subcommittee on Research in the Engineering Field.

R. L. Moore has succeeded Mr. Hill as chief of the Engineering Design Division.

Mr. Hill and Mr. Moore are members of the Society for Experimental Stress Analysis.

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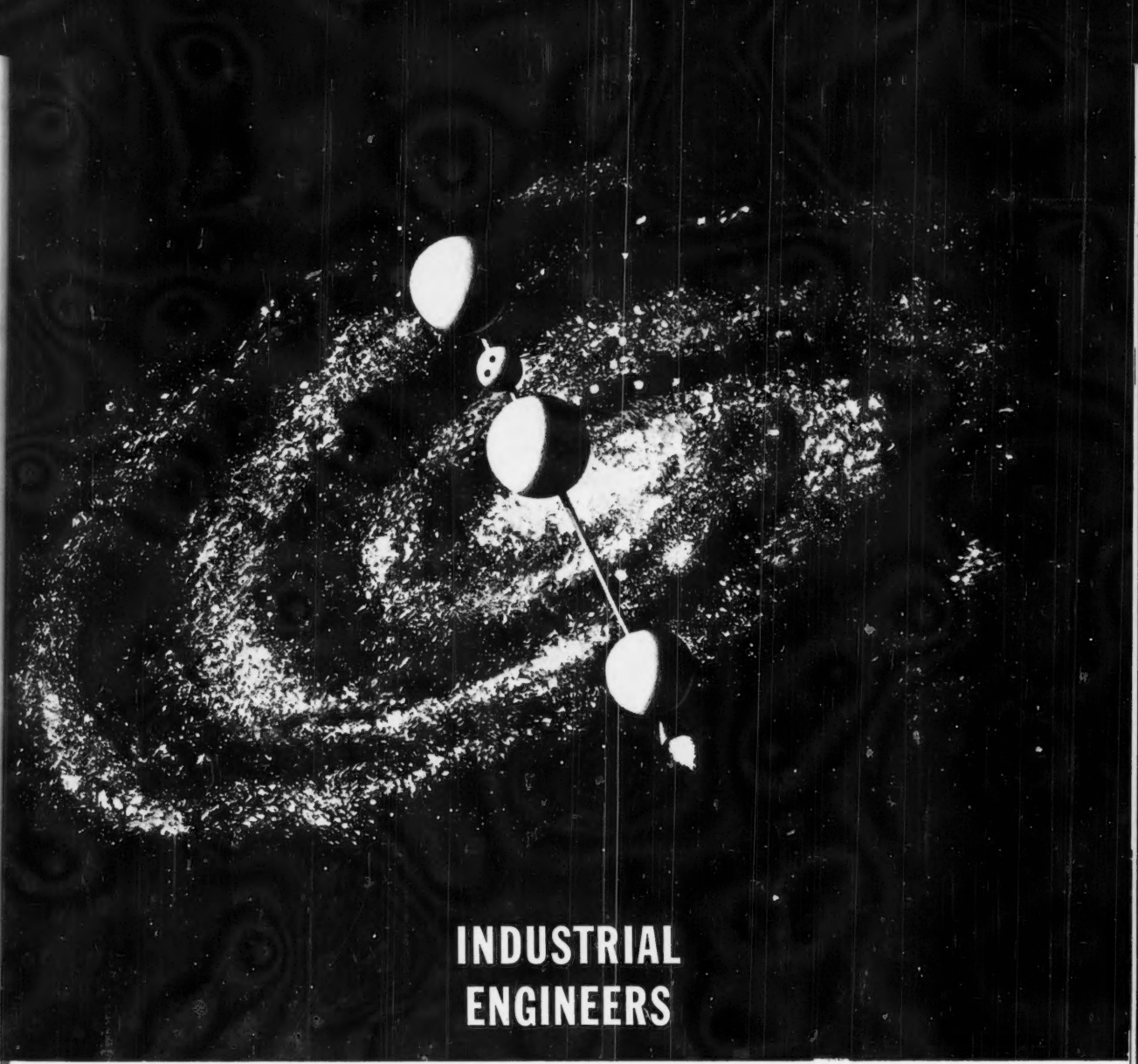

INDUSTRIAL ENGINEERS

Artist's conception of fusion-photon intergalactic space vehicle

If you are an experienced industrial engineer capable of contributing imaginative solutions to advanced manufacturing problems, you will certainly want to consider carefully one of the immediate positions available at Convair/San Diego.

If you have a degree in industrial engineering and several years of aircraft or missile experience, that is most desirable. However, a degree in a related engineering field and a background in another assembly or fabrication industry will be acceptable.

The men selected will be responsible for methods, plant and product layout, facilities utilization and processes, manpower control, and cost reduction. They must be capable of directing small groups of technical specialists assigned to specific problems in the manufacture of conventional and space vehicles.

A prompt interview will be arranged with qualified respondents. Please direct your resume to Mr. M. C. Curtis, Industrial Relations Administrator-Engineering, Convair/San Diego, 3950 Pacific Highway, San Diego, California. All inquiries will be acknowledged.

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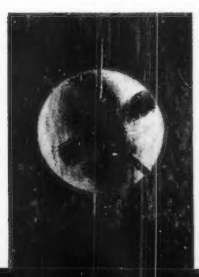

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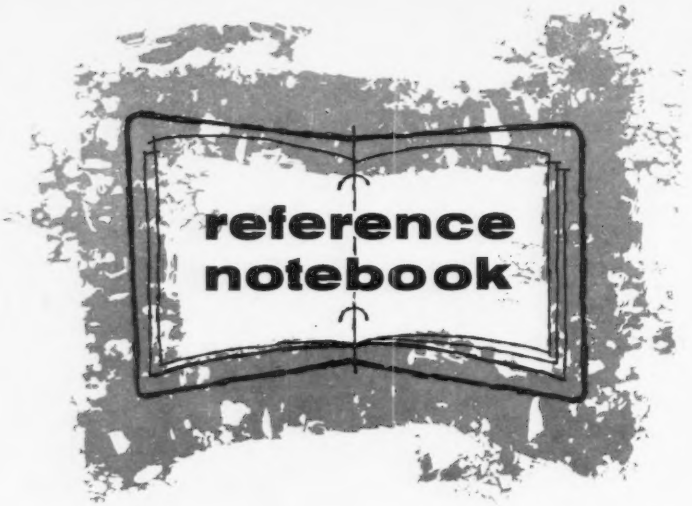

BIBLIOGRAPHY ON THREE-DIMENSIONAL PHOTOELASTICITY 1949–1959

Compiled by
Maurice H. Smith and Mary Lee

INTRODUCTION

The purpose of this bibliography is to present the papers and reports on three-dimensional photoelasticity for the period 1949–59. The principal sources used were: (1) *Applied Mechanics Reviews*, v. 1–13, No. 3, January 1948–March 1960; (2) *Engineering Index*, 1949–1958; and (3) *Technical Abstract Bulletin* (ASTIA: Armed Services Technical Information Agency). Sept. 1, 1957–Mar. 15, 1960.

In addition to these, the reviews of M. M. Frocht (1958 and 1952), R. D. Mindlin (1951) and G. L. Gaudfernau (1957) were examined for references on three-dimensional photoelasticity.

The literature for the period 1939–48 is covered by the bibliography of D. C. Drucker in the *Handbook of Experimental Stress Analysis*, edited by M. Hetenyi (1950), and for the period 1930–38 in the review by R D. Mindlin, in the *Journal of Applied Physics*, v. 10, April and May, 1939.

Some two-dimensional papers are included in the present check list, especially in the field of dynamic and thermal stress determination.

Following a listing of reviews and a list of books, the main body of the bibliography consists of a listing of papers and reports arranged alphabetically by the first author.

Based on Literature Search No. 17 published in April 1960 by the The James Forrestal Research Center Library, Princeton University, Princeton, N. J.

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Photoelasticity and photoplasticity. (Presented at First Symposium on Naval Structural Mechanics, Stanford University, Calif., August, 11–14, 1958.) *Northwestern Technological Institute.* August 1958, 38 pp. 138 references. (Contract Nonr-122, 801). (ASTIA AD 218,955.)

Frocht, M. M.

Experimental stress analysis. *Handbook of Physics*, edited by E. U. Condon and Hugh Odishaw. New York, McGraw-Hill Book Co., 1958. Part 3, Chapter 6, pp. 3-78–3-96. 70 references.

Gaudfernau, G. L.

Photoélasticité tridimensionnelle, aspects théoriques et experimentaux. *France, Ministère de l'Air, Publications Scientifiques et Techniques* No. 330, 1957, 86 pp. 70 references.

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The growth and present state of three-dimensional photoelasticity. *Applied Mechanics Reviews*, vol. 5, No. 8, August 1952, pp. 337–340. 43 references. Supplementary communication, v. 6, No. 6, June 1953, pp. 267.

Mindlin, R. D.

Development of mathematical theory of three-dimensional photoelasticity. *Applied Mechanics Reviews*, v. 4, No. 10, October 1951, pp. 537–539. 35 references.

Drucker, D. C.

Three-dimensional photoelasticity. *Handbook of Experimental Stress Analysis*, edited by M. Hetenyi. New York, John Wiley & Sons, 1950. Chapter 17, Part II, pp. 924–965; Bibliography (References 129–177), pp. 972–976.

Dolan, T. J., and Murray, W. M.

Photoelasticity. Part I, Fundamentals and two-dimensional applications. *Handbook of Experimental Stress Analysis*, edited by M. Hetenyi. New York, John Wiley & Sons, 1950. Chapter 17, Part I, pp. 828–924; Bibliography (References 1–128), pp. 965–972.

Mindlin, Raymond D.

Review of the photoelastic method of stress analysis. *Journal of Applied Physics*, v. 10, April and May 1939, pp. 222–241 and 273–294. 200 references.

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A treatise on photoelasticity. London, Cambridge University Press, 1957. 720 pp. (2nd ed.)

Durelli, A. J., Phillips, E. A., and Tsao, C. H.

Introduction to the Theoretical and Experimental Analysis of Stress and Strain. New York, McGraw-Hill Book Co., 1958, 498 pp.

Föppl, L. and Mönch, E.

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Frocht, Max Mark

Photoelasticity. New York, John Wiley & Sons, 1941–48. 2 vols. 411; 505 pp.

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La photoélasticité. Paris, Dunod, 1947. 419 pp.

PUBLISHED PAPERS AND RESEARCH REPORTS

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On the use of ethoxyline resin in three-dimensional photoelasticity for the freezing technique (in French). *Comptes Rendus, Academie des Sciences.* Paris, v. 233, No. 16, October 1951, pp. 846–847.

(*Continued Next Month*)

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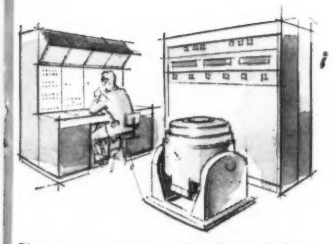

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†US Patent #2,873,341

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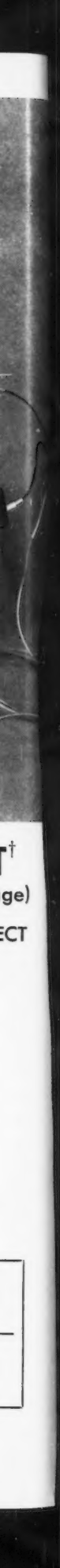
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